SF 298 MASTER COPY KEEP THIS COPY FOR REPRODUCTION PURPOSES

REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
12/31/95

3. REPORT TYPE AND DATES COVERED
Final 1 Nov 92 - 31 Oct 95

4. TITLE AND SUBTITLE
Center of Excellence in Rotorcraft Technology

5. FUNDING NUMBERS
DAAL03-93-G-0002

6. AUTHOR(S) R.G. Loewy, D.A. Peters, J.V.R. Prasad, L.N. Sankar, D.P. Schrage, E.A. Armanios, V.L. Berdichevsky, A.J. Calise, S.V. Hanagud, D.H. Hodges, G.A. Kardomateas, N.M.Komerath

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Georgia Institute of Technology
School of Aerospace Engineering
Atlanta, Georgia 30332-0150

8. PERFORMING ORGANIZATION REPORT NUMBER
E-16-M66

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 30593.41-EG-RW

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

19960521 015

13. ABSTRACT *(Maximum 200 words)*
Georgia Tech's research investigations during the reporting period focused on several analytical and experimental tasks in rotorcraft technology. In the area of Rotorcraft Aerodynamics, work contined on the development of numerical formulations for prediction of viscous flow over rotors and rotor-body combinations without resort to empirical or Lagrangian-based formulations for capturing the tip vortex. Experimental work in transient aerodynamic interactions were aimed at a new capability for, among others, a detailed study of flow separation and reattachment using a basic rotor/wing interaction experiment. Inthe area of Rotor Dynamics & Aeroelasticity, investigations focused on rotor vibration and trim with advanced finite-state wake aerodynamics. In the area of Structures and Materials, dynamic modeling of composite beams was investigated including the edge-zone behavior. Research in robust control theory was devoted to exploring robustness and controller order reduction issues related to the design of rotorcraft flight control systems, development of synthesis techniques for designing full envelope flight controllers without the need for gain scheduling, and neural network based theoretical development and numerical investigation of a direct adaptive tracking control architecture.

14. SUBJECT TERMS
Rotary Wing Aircraft Technology.

15. NUMBER IF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

AUTHORS:
D.P. Schrage
E.A. Armanios
V.L. Berdichevsky
A.J. Calise
S.V. Hanagud
D.H. Hodges
G.A. Kardomateas
N.M. Komerath
R.G. Loewy
D.A. Peters
J.V.R. Prasad
L.N. Sankar

U.S. ARMY RESEARCH OFFICE

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF AEROSPACE ENGINEERING

TABLE OF CONTENTS

I. Aerodynamics Task 2 (AD2)

First-Principles Based Prediction of Rotorcraft Aerodynamics

Principal Investigator:	L. N. Sankar
Participants:	Dr. Vasu Kaladi, Post-Doctoral Researcher; Mr. Nathan Hariharan, Ms. Ping Chen Graduate Research Assistants

Research Goals

The goal of this research effort is the development of numerical formulations that can predict viscous flow over rotors and rotor-body combinations without resort to empirical or Lagrangean based formulations for capturing the tip vortex.

Summary of Work Done:

1. A 3-D compressible Navier-Stokes solver that is third order accurate in time, and fifth order accurate in space is available. The high spatial accuracy of this solver allows it to capture helicopter and fixed wing tip vortices across a very small number of points. This capability of capturing the tip vortices from first principles is essential to first principles based simulation of blade vortex interactions, and for studying advanced blade tips.

The mathematical formulation behind this approach is given in detail in the Ph. D. dissertation of Dr. Nathan Hariharan and in several AIAA papers and AHS Conference proceedings cited at the end of this report.

Figure 1 shows the surface pressure distribution over a UH-60A rotor in hover, computed using Nathan Hariharan's flow solver. The surface pressure distribution at several radial stations is seen to be well predicted. Figure 1 also shows the evolution of the tip vortex for this rotor. It is seen that the fifth order spatially accurate scheme captures the first 180 degrees of the tip vortex well, even though a coarse grid with less than 250,000 cells was used.

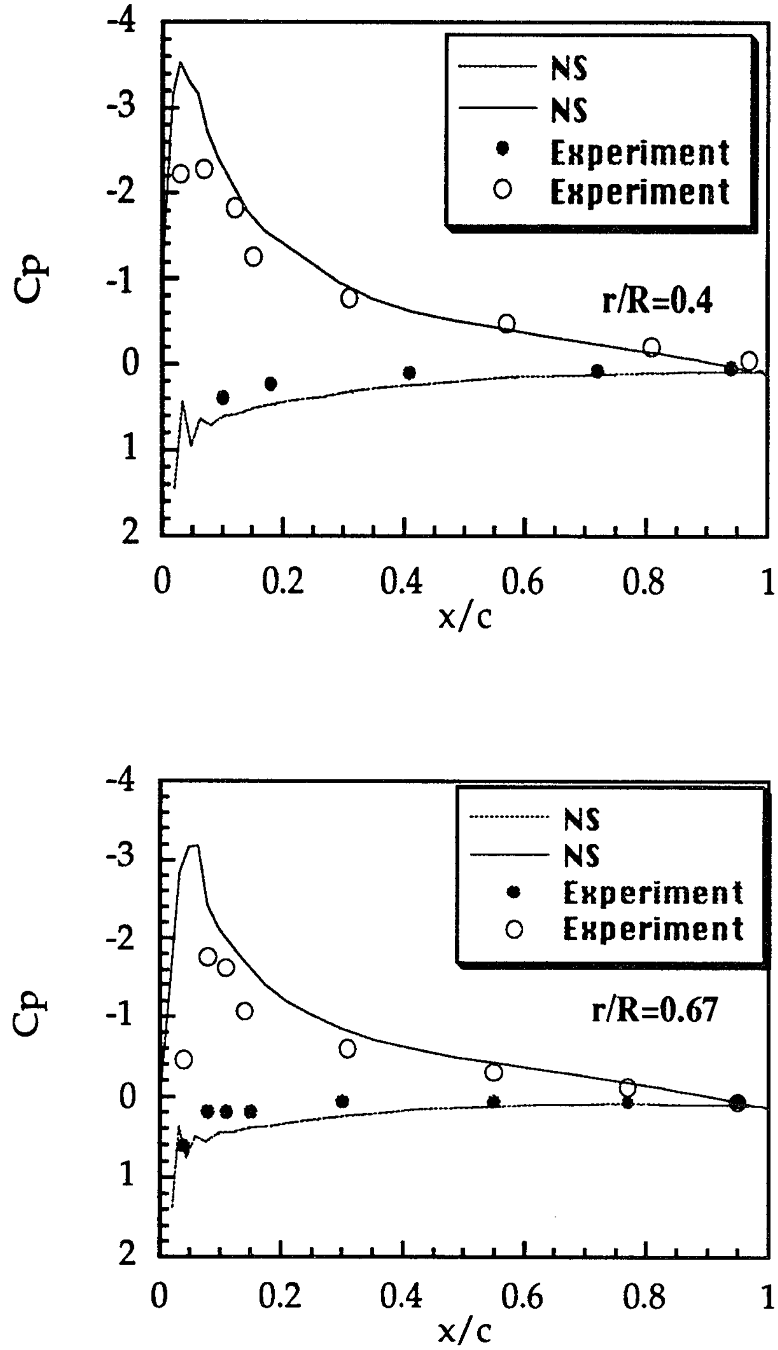
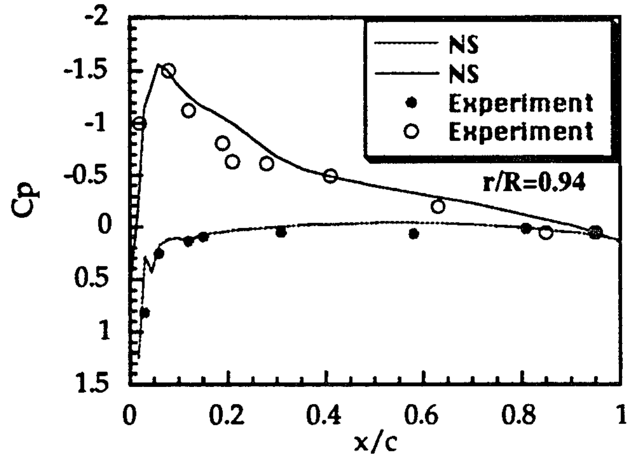


Figure 1. Surface Pressure Distribution over a UH-60A Rotor in Hover



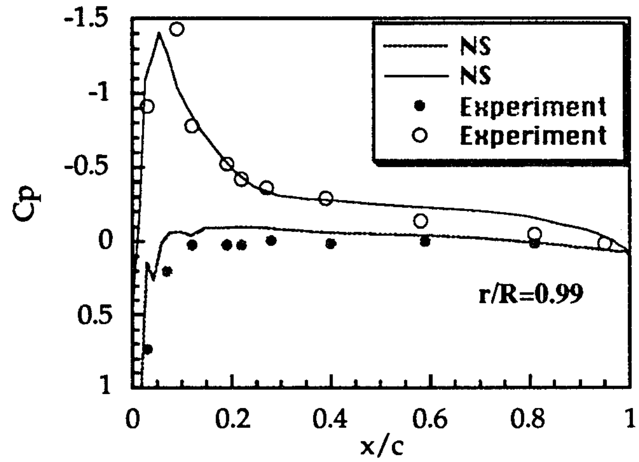


Figure 1 (Continued)

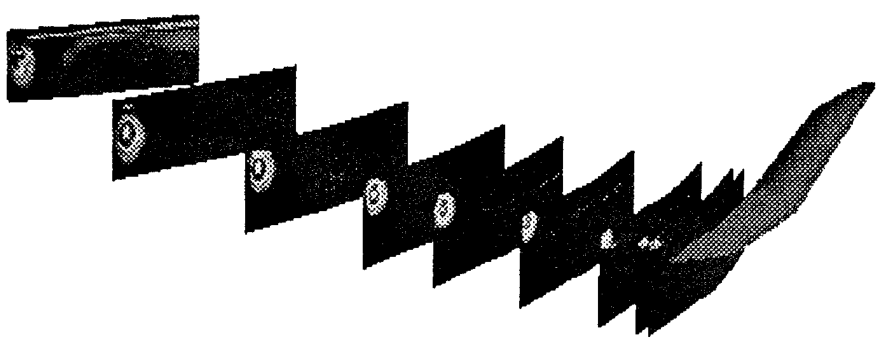
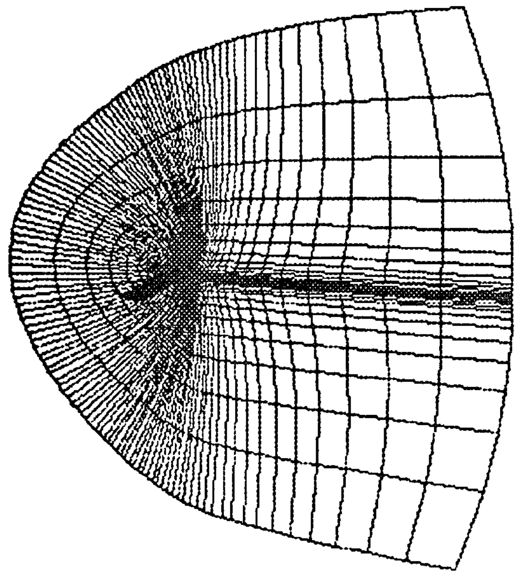


Figure 1. Evolution of the Tip Vortex for a UH-60A rotor in Hover

This analysis has also been validated by computing the velocity field inside the core of a tip vortex shed by a lifting wing. In addition to the surface pressure distributions, both the axial and normal velocity fields have been accurately captured. The fifth order scheme was demonstrated to be superior to conventional third order schemes, as shown in figures 2 below.

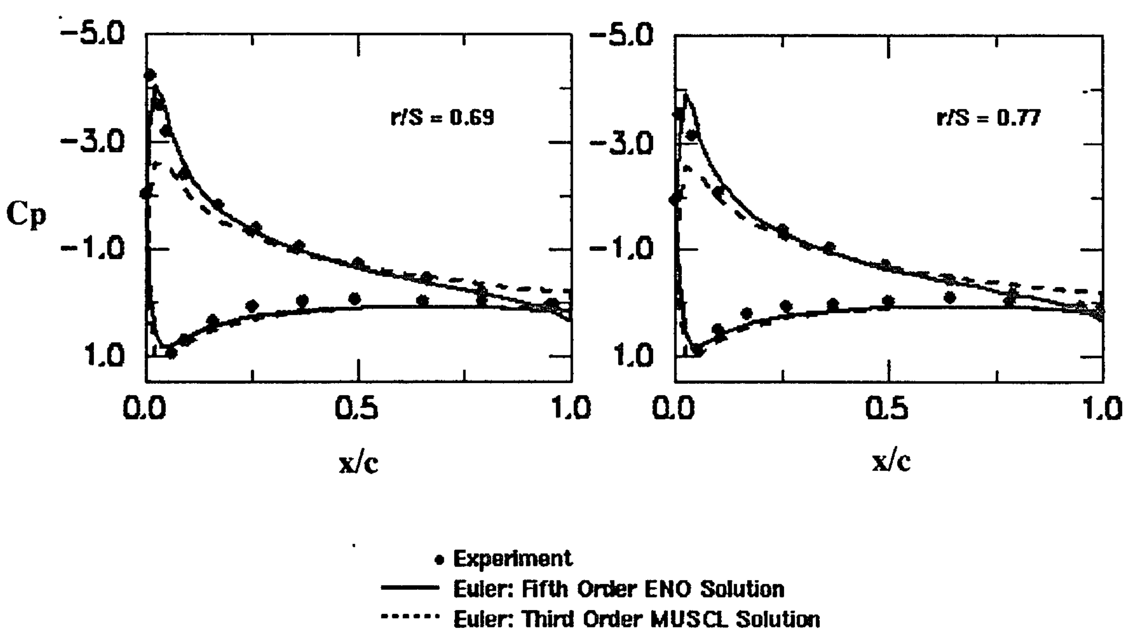
GRID FOR WING TIP VORTEX STUDIES



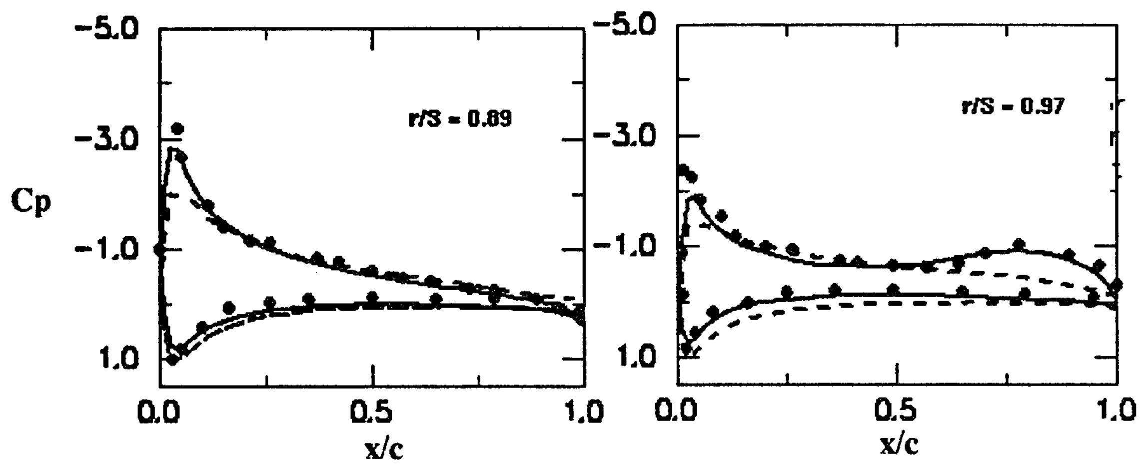
Grid Dimensions:

For Surface Pressure Distribution : 121 * 25 * 31 (ξ, η, ζ)
For Tip Vortex Velocity Distribution: 121 * 40 * 31

SURFACE PRESSURE DISTRIBUTION

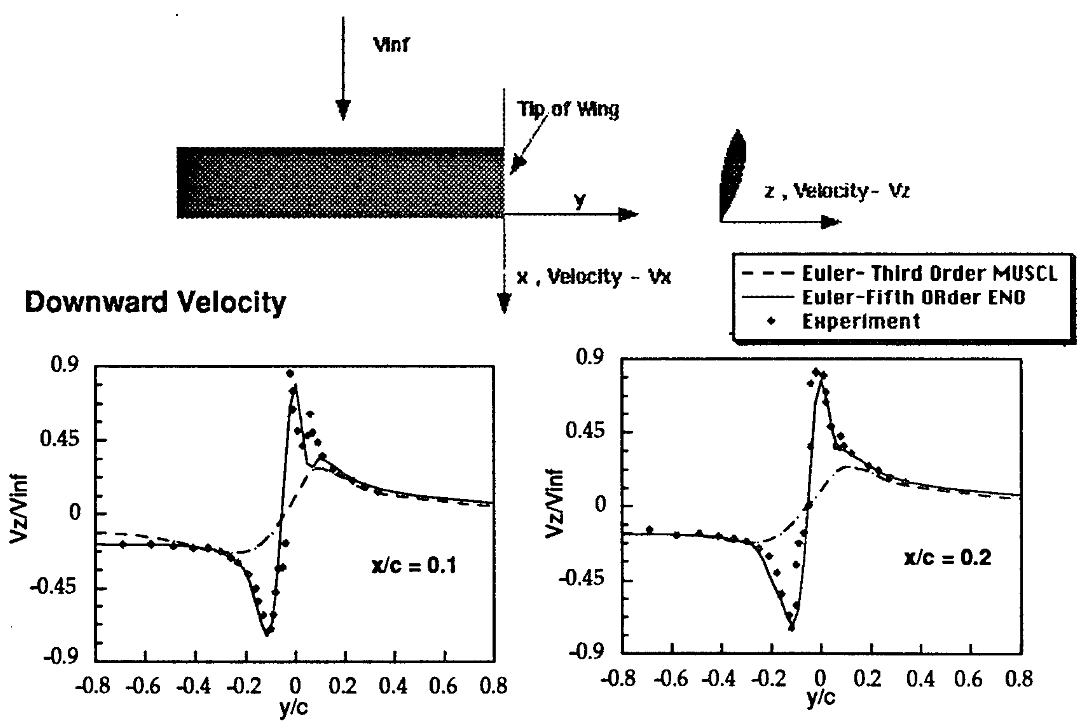


SURFACE PRESSURE DISTRIBUTION



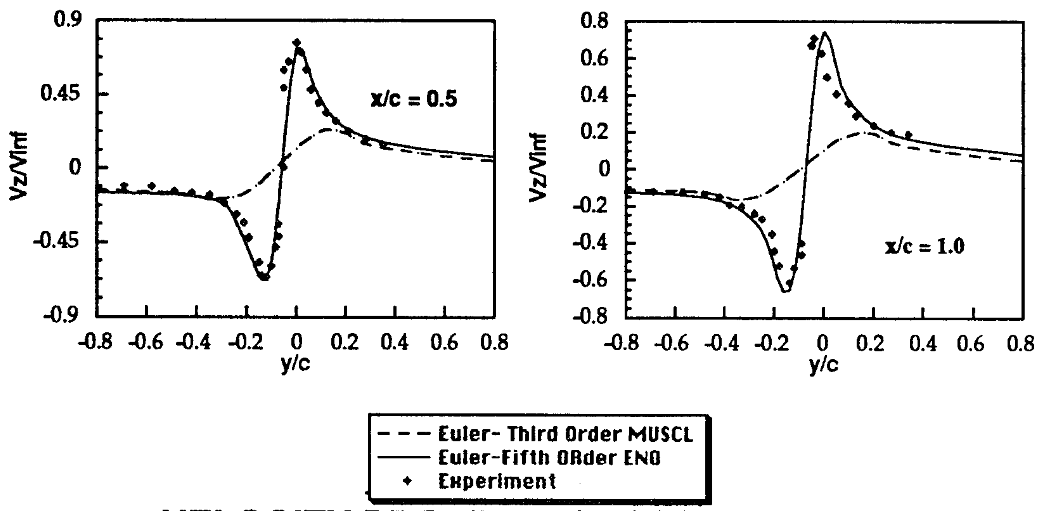
• Experiment
—— Euler: Fifth Order ENO Solution
······ Euler: Third Order MUSCL Solution

VELOCITY PROFILE ACROSS THE TIP VORTEX



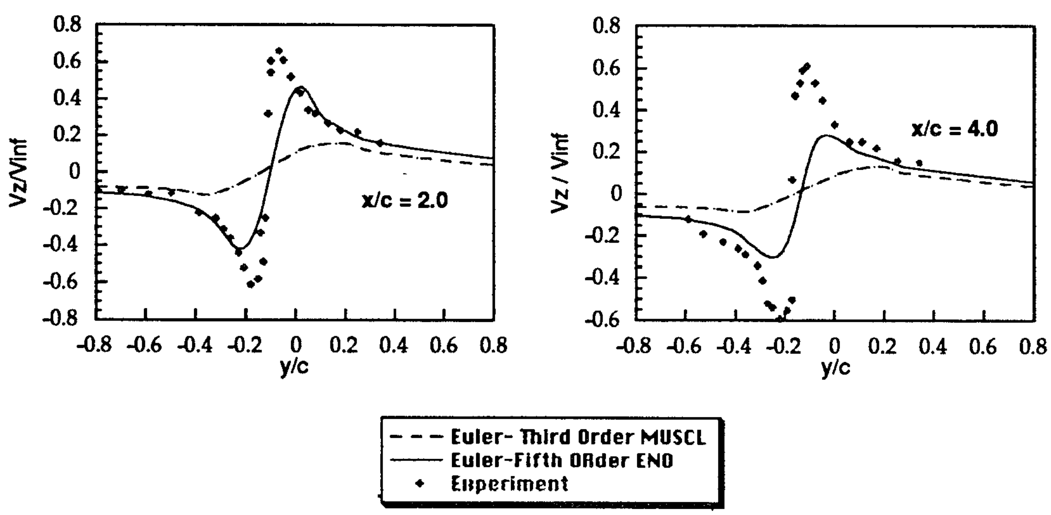
VELOCITY PROFILE ACROSS THE TIP VORTEX

Downward Velocity



VELOCITY PROFILE ACROSS THE TIP VORTEX

Downward Velocity



VELOCITY PROFILE ACROSS THE TIP VORTEX

Axial Velocity

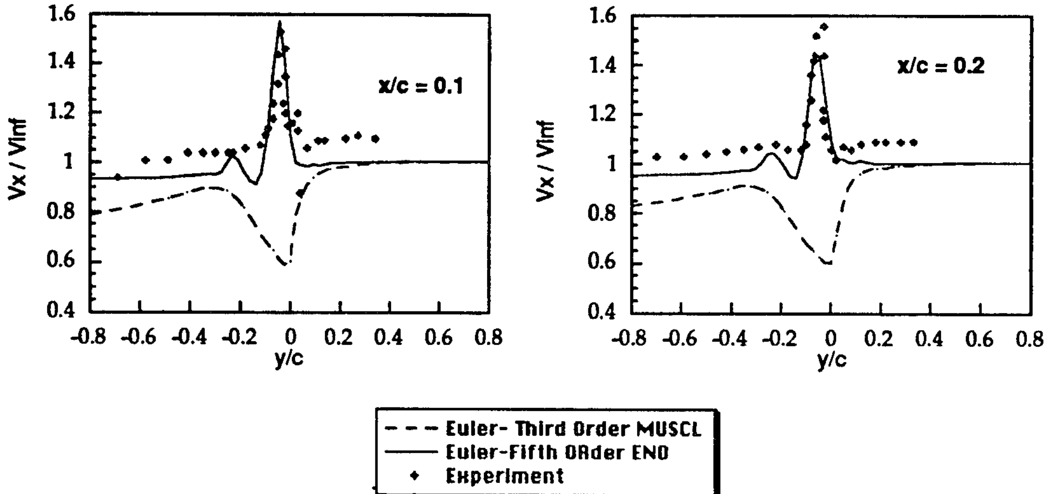


Figure 2. Numerical Studies of Wing Tip Vortex resolution

2. In many practical problems, the interaction between the rotor and other components such as wings and rotors must be modeled. This requires solving the flow equations on several overlapped (or overset grids) that may be in relative motion. Nathan Hariharan developed an overset grid version of his Navier-Stokes solver. It can automatically handle multiple bodies in relative motion. The interpolation of flow properties from one grid to the next is automatically handled by the flow solver without need for externally generated domain connectivity information.

The ability of this solver to model complex rotor airframe interactions was demonstrated in two recent AIAA papers.

A sample application of this code for the rotor-airframe configuration experimentally studied by Komerath and his coworkers is presented. The configuration studied is shown below.

CHIMERA-Fully Interactional Rotor-Body Simulation

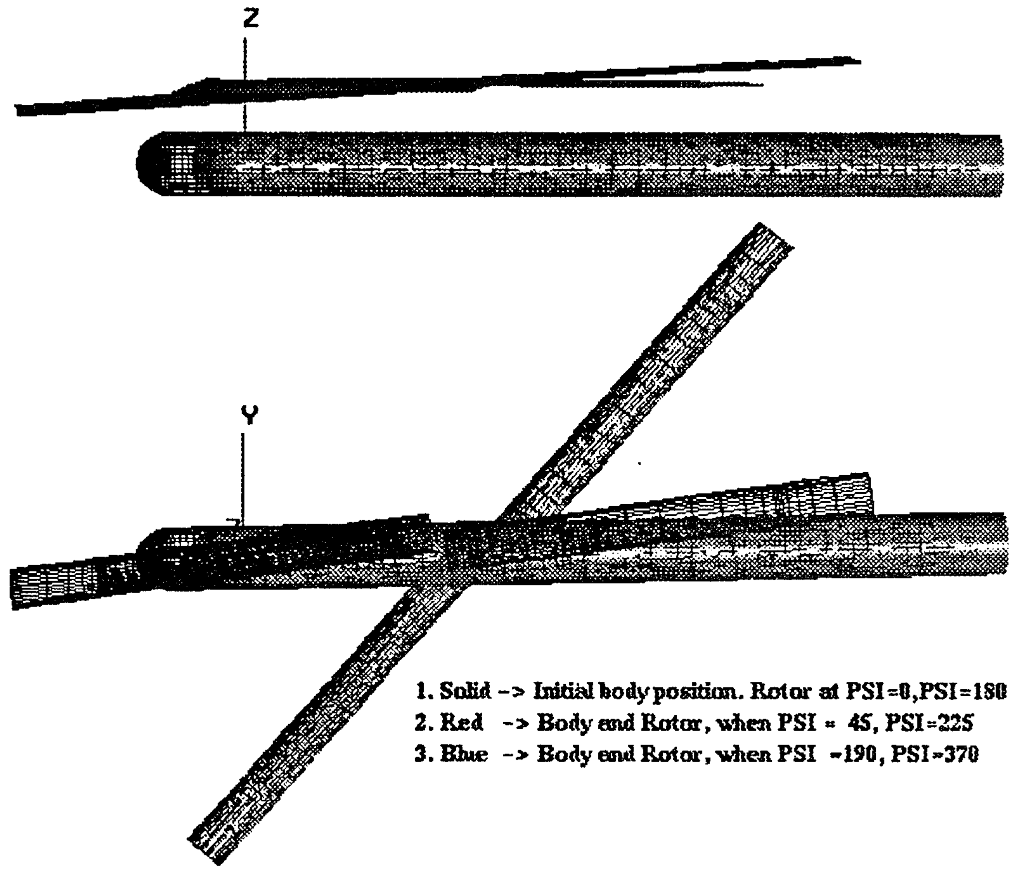


Figure 3 shows the time averaged surface pressure distribution over the fuselage crownline, while figure 4 shows instantaneous surface pressure distributions at selected time levels. Good agreement with experiments is observed, particularly in the aft region of the fuselage. In the front region, where the helicopter blade comes in close proximity to the fuselage, grid density mismatch between the rotor grid and the fuselage grid leads to a degradation in solution accuracy.

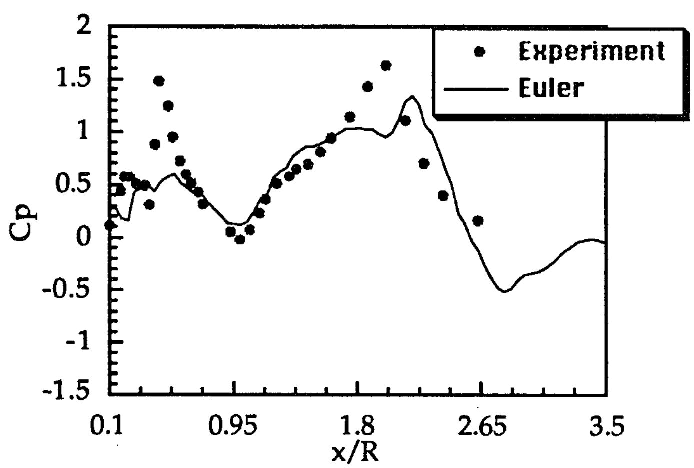


Figure 3. Time Averaged Pressure Distribution over Fuselage Crownline

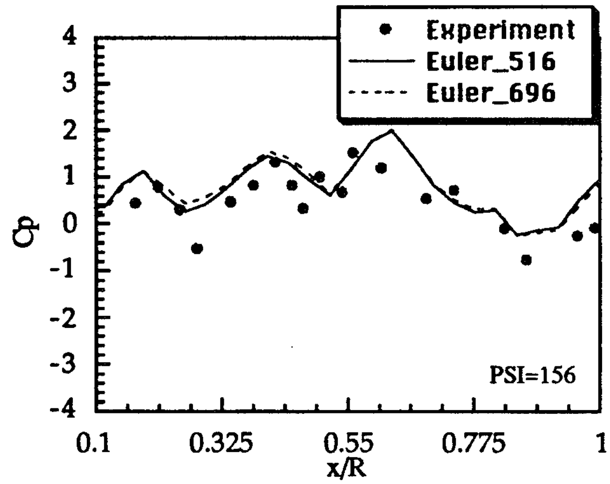


Fig. 4 Instantaneous surface pressure distribution along the crownline of the airframe at two successive half revolutions.

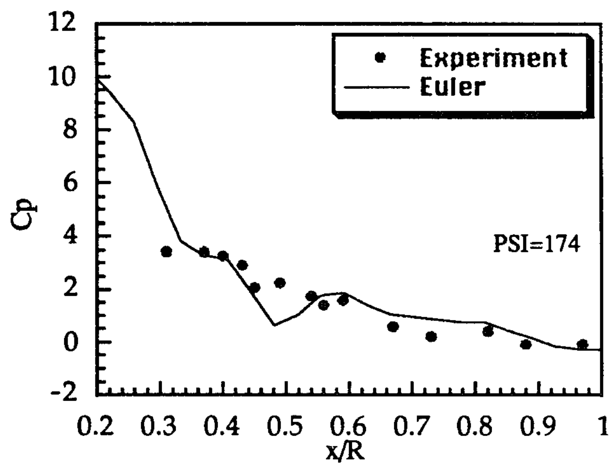


Fig. 4. Continued

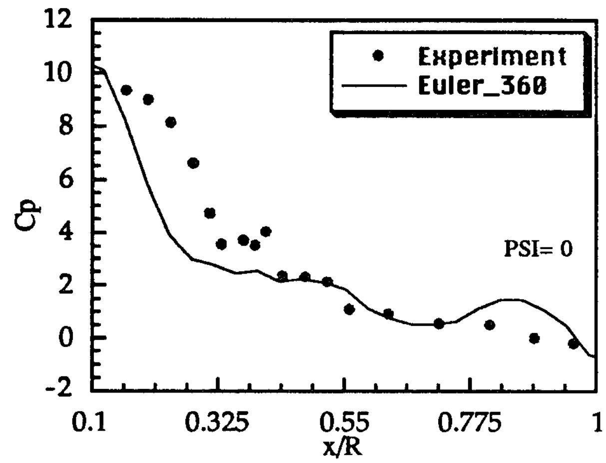


Fig. 4. Continued

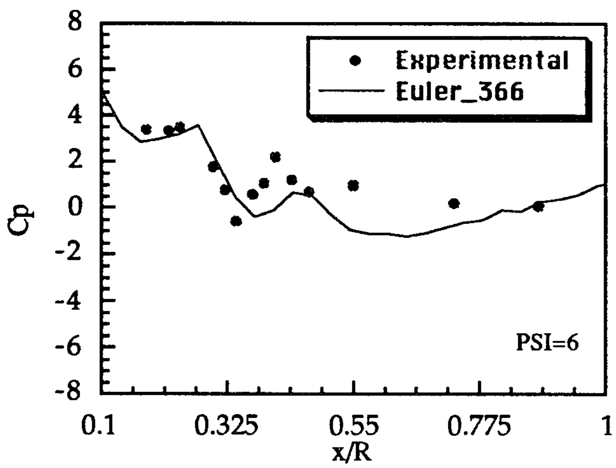


Fig. 4. Concluded

3. Three dimensional Navier-Stokes simulations require several hours of supercomputer time, and can literally take weeks to run on the workstations routinely used in the helicopter industry. If the idle processor power of these machines can somehow be harnessed and combined, then computational performance comparable to supercomputers may be achieved on workstation clusters.

Dr. Ashok Bangalore developed a 3-D Navier-Stokes solver for isolated multi-element rotors and rotors with slats, that are distributed over a number of workstations. Each workstation is responsible for updating the solution only in a small number of zones. The boundary conditions that need to be exchanged between the zones (and machines), as well as the overall synchronization of the time marching process was handled using a set of library routines called parallel virtual machine (PVM). These are FORTRAN callable routines written in C. PVM

versions of the rotor solver was demonstrated both on a small cluster of HP workstations as well as an IBM SP2 parallel supercomputer.

Dr. Bangalore's flow solver, and the PVM implementation are described in a number of recent research publications.

External Interactions :

Dr. Jim Narramore of Bell Helicopter Textron Inc. , Dr. Ahmad Hassan of MDHC, Dr. Brian Wake of UTRC and Dr. Ramachandran of U. S. Army Aeroflightdynamics Directorate have received recent versions of Nathan Hariharan's fifth order accurate flow solver for isolated rotors in forward flight. Other organizations such as Ohio State University (Prof. Herbert) and Lockheed Aeronautical Systems Co. (Dr. K. Viswanathan, Dr. P. Raj) have acquired our analyses and are applying them to non-rotorcraft applications.

Papers Presented:

1. Bangalore, A. and Sankar, L. N., "Numerical Analysis of Aerodynamic Performance of Rotors with leading Edge Slats," AIAA paper 95-1888, Proceedings of the AIAA 13th Applied Aerodynamics Conference, June 19-22, 1995.

2. Hariharan, N. and Sankar, L. N., "Application of ENO Schemes to Rotor Wing Problems," AIAA paper 95-1892, Proceedings of the AIAA 13th Applied Aerodynamics Conference, June 19-22, 1995.

3. Bangalore, A., Tseng, W. and Sankar, L. N., "A Multizone Navier-Stokes Analysis of Dynamic Lift Enhancement Concepts," AIAA Paper 94-0164; To appear in the Journal of Computational Mechanics.

4. Hariharan, N., Sankar, L. N., "Numerical Simulation of Rotor-Airframe Interaction," AIAA Paper 95-0194, 33rd AIAA Aerospace Sciences Meeting, Reno, NV, January 1995.

5. Bangalore, A., Latham, R.L. and Sankar, L.N. "Numerical simulation of viscous flow over rotors using a distributed computing strategy", AIAA Paper 95-0575, 33rd AIAA aerospace sciences meeting, Reno, NV, January 1995. To appear in AIAA Journal.

6. Srinivasan, G. R. and Sankar, L. N., "Status of Euler and Navier-Stokes CFD Methods for Helicopter Applications," Proceedings of the 2nd International Aeromechanics Specialists' Conference, Bridgeport, CT, October 11-13, 1995.

7. Hariharan, N., Sankar, L. N., Russell, J. and Chen, P., "Numerical Simulation of the Fuselage-Rotor Interaction Phenomenon," AIAA Paper 96-0672.

8. Bangalore, A. and Sankar, L. N., "Forward Flight Analysis of Slatted Rotors using Navier-Stokes Methods," AIAA Paper 96-0675

Aerodynamics Task AD3. Experiments on Transient Aerodynamic Interactions

Narayanan Komerath, Robert Funk, Urmila Reddy, Raghav Mahalingam

Statement of the Problem

This Task aimed at a new experimental capability for resolving transient aerodynamic interaction phenomena. The focus is on the understanding of three-dimensional, unsteady vortex-dominated flows typical of rotorcraft. A secondary objective, that of developing large-area velocity measurement techniques, for rotorcraft, was combined with the volumetric velocity measurement work of the Augmentation Task RUA-2 after the first year, and is discussed in that report. Work on wake-induced flow separation, separated flow effects on the rotor wake, and on rotor/airframe vortex interaction from the previous Aerodynamics Interaction Task was also written up and published during this grant period.

Originally, two experimental configurations were proposed: a full-span wing / rotor configuration to study wake interaction with the lifting surface, and a tail boom model under a rotor to study circulation control techniques at large yaw angles in the wind tunnel. The latter experiment was greatly reduced in scope following proposal review, and was discontinued after the first series of tests following the recommendations of the Army Review Panel, with the concurrence of the Executive Advisory Board. We did obtain a set of flow visualization and surface pressure data with a cylindrical boom in the wake of the rotor over a range of yaw angles, but did not reach the point of attempting circulation control. The efforts reported here are this on the wake/lifting surface interaction experiment.

Wake/Wing Interaction

Robert Funk's dissertation research focused on the interaction of a rotor wake with a full-span NACA0021 wing in the John Harper Wind Tunnel. The configuration is shown in Fig. 1, below. Much of this work has been presented in an AIAA Paper in January '94, followed by an AHS Forum Paper in June 1995. Subsequent work is being combined with these into a set of two papers being submitted for journal publication. We showed that:

a) Separation of vortex trajectories from the two blades of the rotor, due to the interaction with the lifting surface. We showed by comparison with an isolated experiment that the interaction accounted for most of the trajectory separation. Recently, Mahalingam has developed explanations for the deviation between trajectories based on vortex interactions; these will be included in the journal submissions. After exploring several test conditions, we selected a condition where the "more upstream" vortex trajectory actually reversed direction and went down over the leading edge of the wing, while the other trajectory went downstream over the upper surface of the wing. This condition was studied in detail.

b) The separation of vortex trajectories was shown to cause a large once-per-revolution pressure fluctuation on the upper surface. The point is that this has little to do with blade-to-blade differences: our two blades are rigidly fixed to each other, and the measured pressures in previous experiments, close to the rotor disc, have shown blade-to-blade repeatability.

c) Wake impingement on the wing upper surface caused reverse flow over the leading edge of the wing at midspan over the entire cycle.

d) At the same time, pressure and tuft studies showed that the entire lower surface experienced steady separation, essentially from the leading edge to the traling edge. Thus this is a test case which qualifies for download studies.

e) Vortex interaction produced multiple stagnation lines on the wing upper surface, and caused an excursion of localized reverse flow over a substantial chordwise range.

f) Earlier experiments using a helicopter stabilator of aspect ratio <1 (Foley et al., AHS Journal, 1995) had shown what appeared to the steady, 2-D separation downstream of the vortex interaction region. This appeared in the full-span wing experiments as well, at the midspan chordwise plane and at a plane on the retreating blade side (RBS). Clearly, no pathline existed from the leading edge to any surface point downstream of the vortex interaction region in these planes. Detailed studies using surface tufts and laser velocimetry showed that this was a case of 3-dimensional separation: there was strong spanwise flow directed from the advancing blade side (ABS) to the RBS, starting in the vortex interaction region. This velocity also has the same sense as the core axial velocity in the tip vortex. Due to this spanwise flow, chordwise stations downstream of vortex interaction on the upper surface have attached flow. The full spanwise extent of the separation region was mapped out from tuft behavior using video images.

g) The line of demarcation between spanwise flows directed towards the RBS and ABS, is shifted to the ABS side of mispan.

h) Extremes of surface pressure on the RBS of the wing surface are much lower in ampltude than in the case of rotor/cylinder interaction. This is attributed to the stagnation and dissipation of the vortex on the ABS, with the vortex interaction occurring at a shallow angle.

i) Detailed 2-component velocity data were acquired using laser velocimetry in two chordwise vertical planes, one at midspan, and one on the RBS. These data were used to generate vorticity contours in the vertical plane, as functions of rotor azimuth. This showed the vortex progression towards the surface, and its apparent sudden dissipation near the surface. The sudden dissipation is attributed to core stagnation at a station somewhat further off to the ABS.

j) The wake interaction phenomena were shown to the periodic and phase-locked to the rotor to first order accuracy. Note, however, that due to the separation of the vortex trajectories, the interaction phenomena occur more at the rotor frequency than at the blade frequency. Root-mean-square velocity fluctuations about these phase-locked averages showed very repeatable patterns, the highest values occurring in the region of vortex interaction with the surface.

k) The integrated section lift and moment, obtained from the chordwise and spanwise distributions of unsteady pressure, were found to be dominated by the twice-per-revolution (once-per-blade) blade passage effect for this configuration. Note that this effect is felt all over the wing, as opposed to the once-per-revolution vortex effect which is limited to a local region.

l) Large negative lift coefficients based on the integrated pressures were explainable only by the high stagnation pressure due to the rotor wake on the upper surface.

These measurements constitute the first comprehensive flow study of a wing-rotor interaction in the open literature, and the velocity measurements are especially high-fidelity, using an unprecendented 100,000 data values per velocity component, per measuring location to generate stable averages with 1-degree rotor azimuth resolution. The detailed unsteady pressure map is also unprecedented, and the finding of 3-D separation on the upper surface was unsuspected before this work. Figure 1(b) shows a simplified model of our present understanding of the wing/rotor interaction.

Journal Papers During this Period

1. Affes, H., Conlisk, A.T., Kim, J.M., and Komerath, N.M., "A Model for Rotor Tip Vortex - Airframe Interaction, Part 2: Comparison with Experiment". AIAA Journal, Vol. 31, No. 12, p. 2263-2273, December 1993.
2. Kim, J-M., Komerath, N.M., and Liou, S-G., "Vorticity Concentration at the Edge of

Task AD3: Komerath et al.

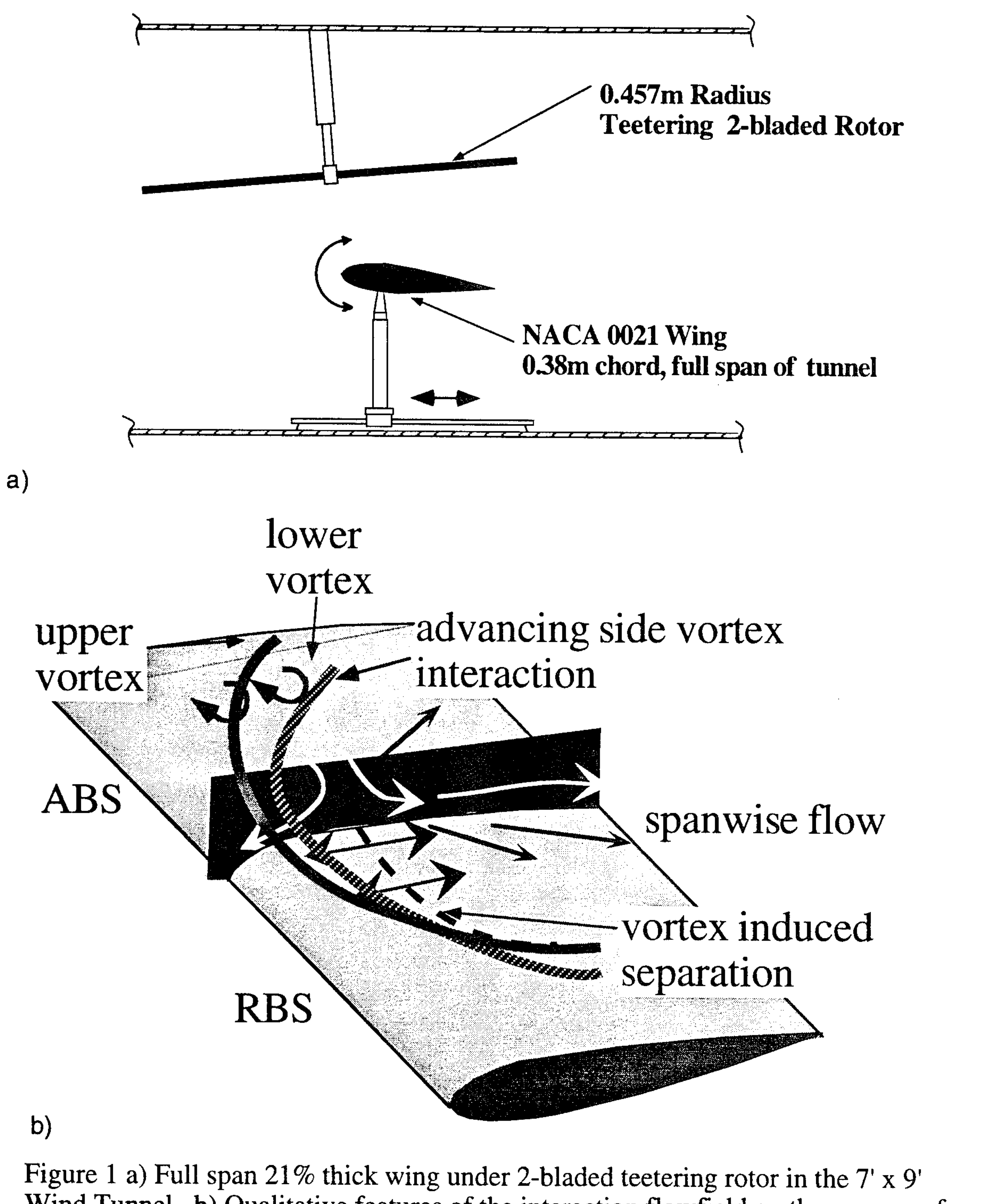


Figure 1 a) Full span 21% thick wing under 2-bladed teetering rotor in the 7' x 9' Wind Tunnel. b) Qualitative features of the interaction flowfield on the upper surface.

the Inboard Vortex Sheet". Journal of the American Helicopter Society, Vol. 39, No.2, p.30-34, April 1994.

3. Komerath, N.M., Kim, J.M., Liou, S.G., "Rotor Wake Interaction with Separated Flow". Invited Paper, Mathematical and Computer Modelling, Special Issue on Rotorcraft, Vol. 18, No. 3/4, pp. 73-87, Pergamon Press, October 1993.
4. Kim, J.M., and Komerath, N.M., "Summary of the Interaction of a Rotor Wake and a Circular Cylinder". AIAA Journal Vol. 33, No. 3, March 1995, p. 470-478.

Conference Papers

1. Kim, J-M., Komerath, N.M., and Liou, S-G., "Vorticity Concentration at the Edge of the Inboard Vortex Sheet". Proceedings of the 49th Annual Forum of the American Helicopter Society, St. Louis, MO, May 1993.
2. Kim, J-M., and Komerath, N.M., "Overview of the interaction between a rotor vortex system and an airframe". AIAA Paper 93-3084, 24th Fluid Dynamics Conference, Orlando, FL, July 1993.
3. Affes, H., Conlisk, T., Kim, J.M., and Komerath, N.M., "Computation and Experiments on the Pre-Collision Phase of a Vortex Interacting with a Cylinder. AIAA Paper 93-3080, 24th Fluid Dynamics Conference, Orlando, FL, July 1993.
4. Funk, R., Fawcett, P.A., and Komerath, N.M., "Instantaneous Velocity Fields in a Rotor Wake By Spatial Correlation Velocimetry". AIAA Paper 93-3081, 24th Fluid Dynamics Conference, Orlando, FL, July 1993.
5. Komerath, N.M., Funk, R.B., Crawford, R.G., "Vortex-Induced Transient Separation on a Lifting Surface". AIAA Paper 94-0738, Aerospace Sciences Meeting, Reno, Nevada, Jan. 94.
6. Funk, R.B., Komerath, N.M., "Vortex-Induced Separation on Lifting Surfaces". Proceedings of the 3rd ARO Workshop on Rotorcraft Interactional Aerodynamics, Atlanta, GA. GITAER 94-5, March 1994.
7. Griffin, M.H., Funk, R.B., Komerath, N.M., "Wind Turbulence Measurement Over Large Areas Using Spatial Correlation Velocimetry". Proceedings of the Silver Symposium of the Flight Test Engineers Society, Patuxent River, MD. V-4- V-4-12, August 1994.
8. Funk, R.B., Komerath, N.M., "Rotor Wake Interaction with a Lifting Surface". Proceedings of the American Helicopter Society Annual Forum, Ft. Worth, TX, May 1995.
9. Funk, R.B., Komerath, N.M., "Modern Diagnostics in an Ancient Wind Tunnel". Annual Meeting of the Subsonic Aerodynamic Testing Association, Auburn Hills, MI, June 1995.

PhD Theses

Kim, J.M., "An Experimental Study of the Interaction Between a Rotor Wake and an Airframe With and Without Flow Separation". PhD Thesis, Georgia Institute of Technology, School of Aerospace Engineering, May 1993.

Funk, Robert B., "Transient Interaction Between a Rotor Wake and a Lifting Surface". PhD Thesis, Georgia Institute of Technology, School of Aerospace Engineering, June 1995.

Degrees Granted

1. Griffin, M.H., M.S. 1993
2. Reddy, U.C., M.S. 1994.
3. Capt. Crawford, G., M.S., 1994.
4. Kim, J.M., PhD 1993
5. Funk, R.B., PhD 1995

External Interactions

1. Komerath visited McDonnell-Douglas Helicopter Company in July 1994 and gave a presentation on our work. He had extensive discussions with MDHC personnel including Tom Thompson, and Ram Janakiram.

2. Komerath and Funk visited Bell Helicopter in May 1995, presented and discussed SCV and LDV application to the Bell tiltotor program in their hover facility. Such experiments continue to be planned.

3. Navy engineer Scott Burgess and a colleague were given a live demonstration of the large-area white light SCV. Focused technical discussions were conducted on shipboard application, and detailed test planning was conducted. In the Fall, Mr. John Funk, USN, visited our facilities for further discussions on these tests.

4. Komerath and Funk visited Wright Patterson AFB in October '94 and gave a presentation on rotorcraft research at the Flight Dynamics Division.

5. Komerath and Funk visited Langley Research Center in Nov. '94 and gave presentations on Rotorcraft Research at the Subsonic Aerodynamics Branch, attended by several Army Lab Researchers. Army researchers Susan Gorton and Terry Ghee made presentations on Army Rotorcraft research. This continued our interaction with Terry Ghee about the Counter-Rotating Vortex observations of Kim and their finding in the large-scale rotor tests at Langley by Terry Ghee.

6. Early results on rotor tip vortex core velocities were supplied to Dr. Ken McAllister from the Army labs at Ames Research Center.

7. Komerath sent a letter summarizing possible avenues of participation for GT students in NASA/Army activities to Susan Gorton.

8. Recently, we have been collaborating with Boeing helicopters on application of testing techniques in the Vertol wind tunnel.

II. ROTOR DYNAMICS AND AEROELASTICITY

Rotor Dynamics and Aeroelasticity Task 1 (RDA 1)
Rotor Vibration and Trim with Advanced Finite-State Wake Aerodynamics

Principal Investigator: D. A. Peters
Participants: D. Barwey, Post-Doc; W. M. Cao, M. Johnson,
Rochelle Beaver, Y. R. Li, G. Nichols - GRA's

Objectives
In order to develop advanced rotorcraft technologies and to test the effectiveness of current technologies under battlefield conditions, it is necessary to be able to compute rotorcraft vibrations and response. In order to do this in a real-time simulation, the mathematical models and solutions strategies must be efficient as well as accurate.

The objective of this research task is to develop a wake model and a solution (i.e., trim) methodology that is accurate enough to capture realistic wake phenomena, but that is efficient enough to be used in both preliminary design and simulation calculations. Until now, trim methodologies have been slow and problem-specific. The objective here is to develop a general theory of trim so that an efficient strategy can be designed to operate in real-time simulations.

Approach
The approach in wake modeling is to begin with the finite-state wake model developed in previous ARO-funded research. This model is now being used in several simulation and design programs including FLIGHT-LAB and 2GCHAS. What we are doing in this research is improving it to include three important effects presently not modeled: 1) wake distortion, 2) tip vortex, and 3) flow away from the rotor. These effects are very important in order to obtain accurate rotorcraft vibrations and performance. We are also improving our blade stall model (developed under ARO funding) to include radial flow.

The approach in solution methodologies is to first identify and categorize all existing methodologies and then to generalize them to a complete theory of trim. Next, we will try to unify the existing theories into a single "smart-trim" algorithm that could be applied to any conceivable trim problem. Important methods included in this progress will be "Periodic Shooting" and "Auto-Pilot", developed under ARO sponsorship and now used in many codes around the country including 2GCHAS. The first strategy uses a "smart" trial and error to locate the solution, while the second method "flies" the rotorcraft to a solution.

Accomplishments
During the final period of RDA1, we have completed all of the subtasks. In this report, we summarize our accomplishments since the last progress report and identify how these fit into the overall accomplishment of our goals for the entire Phase III program.

First, we consider the wake-modeling aspect of our work. In the last period of this work both Greg Nichols and Wen Ming Cao have completed their ARO work and their Doctoral Theses. They have both graduated with Doctor of Science degrees. The work of Greg Nichols has continued throughout the period of this work, and he has finished what we set out to accomplish. In particular, Greg set up a very specialized vortex-lattice tool in order to compute induced flow fields for specified circulation distributions. He then successfully showed that, for a skewed cylindrical wake, he could identify the components of the influence coefficients (i.e., the L matrix) and that they were in agreement with the closed form results of dynamic inflow theory both in hover and in forward flight. Next, he allowed the wake of his vortex lattice code to distort in various ways, including the case of tip vortices going above (and then back through) the rotor disk. He successfully showed that he could identify the elements of the L matrix for this distorted case and that the new L matrix then gave blade-vortex interaction effects within the context of the dynamic wake model. Thus, we have successfully demonstrated how a general

vortex lattice code can be used to modify the wake model to include wake distortion. Future work would be for a production wake code to be used in this context on a realistic problem.

The work of Wen Ming Cao has also shown a continuity throughout the course of this research. His task was to extend the inflow model to include all three components of induced flow everywhere in the flow field. This work is now successfully completed. Through the course of the work, he discovered that our original plan for accomplishing this was inadequate. In particular, we had felt that either the velocity potential or the acceleration potential states could be used find the flow everywhere. Dr. Cao discovered that both types of states must be known in order to compute the entire flow field. As it turns out, one must solve an auxiliary set of differential equations to find the other states. These equations have the same coefficients (but different forcing functions) than do the original finite-state equations. This single solution, however, gives the flow everywhere. The velocity potential part is discontinuous inside and outside of the rotor wake, as it should be, and does not reduce do zero within the far wake. It is driven primarily by the shed wake. The acceleration portion of the flow field is continuous and decays in the far field. It is primarily driven by the bound vorticity. Because the finite state model is an actuator disc theory, it assumes that all lift is normal to the rotor disc. Dr. Cao also discovered that, by use of the "warped disk assumption", one can include the effect of inplane loads on the induced flow. The approach is rigorous in hover, and it is a good approximation in forward flight. Comparisons with the vortex lattice code of Greg Nichols confirm the feasibility of the method. These comparisons are made above the disk, at the disk, and below the disk as well as both inside and outside of the wake. Integrals of the Legendre functions along the streamlines are required from infinity to the point desired. All other elements are in closed form.

Another area of research has been in the development of an airloads theory for flexible airfoils. This theory has been the thesis work of Mark Johnson. During the final phase of our work, the model was extended to include compressibility effects. Comparisons with experimental data at large, subsonic Mach numbers has shown the results to be better that the indicial method of Leishman for the cases considered. Thus, we have a complete unsteady airloads model (in either two or three dimensions) that computes lift, moment, drag and all other generalized forces, that includes unsteady free-stream (with reversed flow and circulation control) and stall, and which can be corrected for compressibility effects. This must certainly be one of the major theories necessary to evaluate individual blade control and smart structures applications. Also, Dr. Dinesh Barwey has successfully added the effects of radial (or yawed) flow to our dynamic stall modeling. This allows a full three-dimensional stall treatment to be integrated with the airloads and wake models. Mark Johnson has graduated with his M. Sc. Degree.

Next, we have the results of our trim methodology. In earlier parts of this task, we developed a successful testbed to try out trim strategies; and we developed a completely general "Theory of Trim" that encompasses all methodologies, system equations, and even optimum trim. With this trim theory as the basis, we have been designing alternative trim methodologies. One is the hybrid periodic-shooting, auto-pilot method. In the final phase of our work (involving Si Hao Li and Dr. Dinesh Barwey), we have added the concept of a discrete auto-pilot to the available methods. Comparisons with other methods have shown that the discrete auto-pilot works even when there are several zero eigenvalues in the system (such as in free flight). This has now broadened the possibilities of trim algorithms that can be designed.

Finally, our work on trim has included the development of a theory of "Fast Floquet Theory and Trim" for rotor-body systems with one or more rotors, each rotor having a set of identical blades. The results have shown that trim and Floquet theory can be done with a factor of savings equal to at least the number of blades. For some rotor systems, the savings has been as much as a factor of 20 in both trim and stability. Amazingly, the savings come at absolutely no cost of overhead, and any existing code can be converted to the fast method with only a few lines of coding changes. Rochelle Beaver has worked on this project and has graduated with her M. Sc. Degree.

Interactions

During this final period of the grant, several important technical interactions have taken place. First, Professor Gopal Gaonkar of Florida Atlantic University has combined our Fast Floquet Theory with his own massively parallel computational methodologies, and this has allowed him to perform Floquet analysis on systems with over 500 states. This is a new world record and shows promise for very large systems. Second, out flexible airfoil theory has been adopted by several investigators who are interested in individual blade control through smart structures. These groups include: Professor Aditi Chattopadyay of Arizona State, Professor Erian Armanios of Georgia Tech, Professor Sathya Hanagud of Georgia Tech, Professor Robert Loewy of Georgia Tech, AFOSR Proposal Team, Purdue, and Professor Earl Dowell, Duke University. During the course of this work, we have also traveled and given presentations to: Army Aeroflightdynamics Lab, McDonnell Douglas Helicopter, Advanced Rotorcraft Technologies, and Sikorsky.

Significance

The significance of these accomplishments is that Army and Industry design and simulation codes, when modified to include these new models and methodologies, are able to include realistic aerodynamic details in a very efficient manner such that important design decisions can be made at an early point and such that real-time simulations can affect battlefield decisions in a timely manner.

Refereed Publications

Peters, David A., "Fast Floquet Theory and Trim for Multi-Bladed Rotorcraft," *Journal of the American Helicopter Society*, Vol. 39, No. 4, October 1994, pp. 82-89.

Peters, David A., Karunamoorthy, Swaminathan, and Cao, Wen-Ming, "Finite-State Induced Flow Models, Part I: Two-Dimensional Thin Airfoil," *Journal of Aircraft*, Vol. 32, No. 2, March-April 1995, pp. 313-322.

Peters, David A., and He, Cheng Jian, "Finite-State Induced Flow Models, Part II: Three-Dimensional Rotor Disk," *Journal of Aircraft*, Vol. 32, No. 2, March-April 1995, pp. 323-333.

Peters, David A., and Barwey, Dinesh, "A General Theory of Rotorcraft Trim", *Mathematical Problems in Engineering*, Fall 1995.

Peters, David A., "Some Observations on the Sinha Approach to Dynamic Response Calculations," *Journal of Sound and Vibration*, Vol. 188, No. 4, December 14, 1995, pp. 617-628.

Paper Presentations and Proceedings

Peters, David A., "Finite-State Airloads for Deformable Airfoils on Fixed and Rotating Wings," Aeroelasticity and Fluid/Structures Interaction Problems, a Mini-Symposium, ASME Winter Annual Meeting, Chicago, November 6-11, 1994, AD - Vol. 44, pp. 1-28.

Peters, David A., and Barwey, Dinesh, "A General Theory of Rotorcraft Trim," 36th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, New Orleans, April 10-12, 1995, Paper No. 95-1451.

Peters, David A., "Fast Floquet Theory and Trim for Multi-Bladed Rotorcraft," Proceedings of the 51st Annual National Forum of the American Helicopter Society, Ft. Worth, May 7-9, 1995.

Paper Presentations and Proceedings (cont'd)

Peters, David A., and Li, Si-Hao, "A Combined Periodic-Shooting, Auto Pilot Technique for Rotorcraft Analysis," *Computational Mechanics '95*, Proceedings of the International Conference on Computational Engineering Science, Mauna Lani, Hawaii, July 30-August 3, 1995, pp. 654-659.

Schmitt, John M., Bayly, Philip V., and Peters, David A., "Stabilization of Periodic Flap-Lag Dynamics in Rotor Blades," ASME 15th Biennial Conference on Vibrations and Noise, Boston, September 17-21, 1995; and AHS 2nd International aeromechanics Specialists' Conference, Bridgeport, CT, October 11-13, 1995.

Peters. David A., Barwey, Dinesh, and Johnson, Mark J., "Finite-State Airloads Modeling with Compressibility and Unsteady Free-Stream," Sixth International Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, UCLA, November 8-10, 1995.

Barwey, Dinesh and Peters, David A., "Modeling of Radial-Flow Stall Effects for Rotor Dynamics", Sixth International Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, UCLA, November 8-10, 1995.

Peters, David A. and Cao, Wenming, "Off-Rotor Induced Flow by a Finite-State Wake Model", 37th AIAA SDM Conference, Salt Lake City, April 15-17, 1996, Paper No. 96-1550.

Peters, David A. and Beaver, Rochelle D., "Application of Fast Floquet Theory to Rotor Flap Response with Dynamic Inflow", AIAA Dynamics Specialists' Conference, Salt Lake City, April 18-19, 1996, Paper No. 96-1216.

Peters, David A., Bayly, Philip, and Li, Sihao, "A Hybrid Periodic-Shooting, Auto-Pilot Method for Rotorcraft Trim Analysis", Proceedings of the 52nd Annual National Forum of the American Helicopter Society, Washington, DC, June 4-6, 1996.

de Andrade, Donizeti, da Silva Correa, Manoela, and Peters, David A., "New Correlation of Experimental Flap-Lag-Torsion Damping", Proceedings of the 52nd Annual National Forum of the American Helicopter Society, Washington, DC, June 4-6, 1996.

Theses

Johnson, Mark James, *Finite-State Airloads for Deformable Airfoils and Rotating Wings*, Master of Science Thesis, Washington University, August 1995.

Nichols, Gregory, *Finite-State influence Coefficients for a Distorted Wake from a Vortex-Lattice*, Doctor of Science Thesis, Washington University, December 1995.

Cao, Wenming, *State-Space Unsteady Aerodynamic Theories for Rotating Wings in Two and Three Dimensions*, Doctor of Science Thesis, Washington University, December 1995.

Beaver, Rochelle D., *Applications of Fast Floquet Theory to Rotor Flap Response with Dynamic Inflow*, Master of Science Thesis, Washington University in St. Louis, December 1995.

RDA.2 Rotorcraft Dynamics and Aeroelasticity Task (RDA2) Composite Rotor Blade Aeroelasticity with Three-Dimensional Aerodynamics

Co-PI's: Dewey H. Hodges and David A. Peters

Background

Rotor aeroelastic response and stability analyses have traditionally been carried out in terms of state-of-the-art nonlinear structural dynamics models but with relatively crude, quasi-steady aerodynamics. However, in recent ARO-sponsored work, it was conclusively demonstrated by two independent analyses that the lead-lag damping for rotor blades in hover is strongly affected by the wake dynamics. First, the nonlinear Hodges and Dowell (1974) blade model was coupled with a three-dimensional panel code with a prescribed wake geometry (Kwon, Hodges, and Sankar, 1991). This method proved to be extremely computationally intensive, but it did demonstrate the importance of three-dimensional unsteady effects. Second, in the late 1980s a three-dimensional unsteady state-space aerodynamic theory for rotors was developed by Peters and He (1988) under ARO sponsorship. The integration of this theory with rotor blade structural dynamics analyses is required in order to analyze the aeroelastic response and stability of rotor systems. Only a limited amount of integration of this theory with rotor blade models has been carried out, but very significant differences between predicted stability with and without the new unsteady theory have been identified. In fact, the finite-state model of Peters and He was used by Peters and De Andrade (1992) with the same Hodges and Dowell (1974) blade model to produce results which are essentially identical to those obtained by Kwon, Hodges, and Sankar (1991), but by means of a much more efficient eigenvalue analysis. So far, however, all the blade analyses with which the new theory has been integrated are of the displacement type and are applicable only to isotopic rotor blades, which lack the elastic coupling possible with composite blades.

Scope of Work

In this task we set out to explore the interdisciplinary field of aeroelasticity by coupling the unsteady aerodynamic model with composite blade models for stability analysis and studying the stability of elastically coupled blades with these models. In order to integrate the new theory with certain composite rotor blade analyses it is necessary to broaden the scope of the integration process to include mixed methods for the structural dynamics modeling. By mixed here we mean a blade analysis with unknowns other than beam reference line displacements and section rotations, such as various strain measures and/or stress resultants. Such theories often have equations whose structures are quite different from those of typical displacement methods (see Hodges, 1990). For example, mixed methods are typically based on systems of first-order equations, as opposed to displacement methods which are based on systems of second and fourth order. Second, mixed methods have inherently simpler expressions for the orientation and velocity variables needed in the aerodynamic theory. Finally, the computational efficiency of mixed methods is largely dependent on the extremely high percentage of zeros in the coefficient matrices of the system equations. For these reasons the integration process was quite challenging, especially because of the need to preserve sparsity in the mixed method for computational efficiency. Our intent was to carry out this integration process without destroying sparsity and other advantages associated with mixed methods.

Summary of Accomplishments

The development of the analysis was accomplished in several stages: (1) single-blade, steady-state structural response in vacuo, including sweep and other geometric parameters; (2) single-

blade structural dynamics with non-aerodynamic loading; (3) incorporation of steady, finite-state induced inflow; and (4) incorporation of unsteady, finite-state induced inflow, allowing the transient response analysis of multi-bladed rotors. It is noted that a modal reduction was not required in order to achieve computational efficiency with the mixed formulation. After the analysis was developed some practical studies were then carried out with the completed model. With this model it is now possible to analyze the aeroelastic stability analysis of composite hingeless rotor with cantilevered blades and several types of advanced configuration parameters, such as tip sweep, an-/dihedral, initial twist, initial curvature, all types of elastic coupling due to the use of composite materials, etc. The division of labor was roughly as follows: The Georgia Tech group, under the direction of Prof. Hodges, concentrated on integration of the mixed method with the finite-state aerodynamics model, which required very close collaboration with Prof. Peters at Washington University.

The work proceeded as follows: The structural analysis and structural dynamics portions of the finite element code were rewritten to incorporate spanwise nonuniformity for modeling realistic blades. At this time the displacement and rotation variables were also recast into a single rotating hub frame, which allows for coupling of blade segments which meet at non-zero angles such as would be needed to model sweep and anhedral effects. Steps (1) and (2) were thus completed using the mixed method of Hodges (1990) in the frequency domain following the work of Fulton (1992) and Fulton and Hodges (1993). This step was validated by calculating the static analysis of rotating composite blades with the new formulation, which consisted of examining the behavior of blades with mid-span sweep. The geometrically-exact formulation avoids many of the problems associated with moderate-deflection theories when treating problems of this nature. To validate this portion of the code, we correlated our results with experimental data that were generated by our rotorcraft center colleagues at the University of Maryland. Our correlation was excellent and demonstrates that a geometrically-exact approach is necessary to predict accurately the natural frequencies of composite blades with swept tips.

Step (3), the addition of steady-state induced inflow, was undertaken next. The steady-state response was then performed for a two-bladed rotor, giving the inflow distribution, displacement field, and stress field of the rotor. After correlation with the published results by de Andrade and Peters, excellent agreement is found for the inflow distribution in the outer 80% span. In the region nearer the rotor center, our results are quite reasonable although they differ somewhat from those of de Andrade and Peters. Displacement and stress results are also quite reasonable.

For step (4), in anticipation of the coupled aeroelastic eigen-problem (estimated to be about 400 degrees of freedom in the eigensystem), a generalized version of the Lanczos algorithm, was written by Mr. Shang, and was adopted to permit treatment of non-symmetric, sparse coefficient matrices. Next, the development of the unsteady aerodynamics model for use with the mixed method was completed. The composite blade modeling was thoroughly validated in other projects, and agreement with the previous work of Fulton was deemed an adequate test of this portion of the analysis. The validation of the aeroelastic model focused on correlation with the torsionally soft experimental data generated by Sharpe at the U.S. Army AFDD, Ames Research Center. There were indications, again, that the geometrically-exact treatment of the beam brought about improvements in the correlation relative to that obtained by other investigators.

This means that now one can study composite hingeless rotors with certain configuration paramters that were not before possible to incorporate in a rigorous way. Thus, some parametric studies were done and the results are contained in the paper that will be presented at the 37th SDM meeting, April 1996. Those results indicate a wealth of possible design parameters, many of which do significantly affect the lead-lag modal damping and the internal loads for a given level of thrust. Obviously, one should not take such a study too seriously until many more aerodynamic phenomena and at least a steady forward flight condition can be incoroporated into

the analysis. The analysis developed, however, appears to be quite accurate for calculation of the structural dynamics and hovering flight aeroelastic stability of composite hingeless rotor blades.

External Interactions

Dr. Hodges has interacted with Dr. Robert Bless, of Lockheed, with Dr. Ruzicka of AFDD concerning 2GCHAS, and some discussions took place with Dr. Robert A. Ormiston concerning the analysis and how it should be exercised. Dr. Peters and his group have interacted with Dr. Ron Duval of ART.

Publications

Refereed Journals:

Hodges, Dewey H.; Chung, Yoon Y.; and Shang, Xiao Y.: "Discrete Transfer Matrix Method for Rotating Beams," *Journal of Sound and Vibration*, vol. 169, no. 2, Jan. 13, 1994, pp. 276 – 283.

Hodges, Dewey H.; and Bless, Robert R.: "Axial Instability of Rotating Rods Revisited," *International Journal of Non-Linear Mechanics*, vol. 29, no. 6, Nov. 1994, pp. 879 –887. (CERT related)

Sujith, R. I.; and Hodges, Dewey H.: "Exact Solution for the Free Vibration of a Hanging Cord with a Tip Mass," *Journal of Sound and Vibration*, vol. 179, no. 2, Jan. 12, 1995, pp. 359 – 361. (CERT related)

Hodges, Dewey H.; and Bless, Robert R.: "On an Analogy Between Beam Contact Problems and Optimal Control Theory with State Constraints," *AIAA Journal*, vol. 33, no. 3, Mar. 1995, pp. 551 – 556. (CERT related)

Hodges, Dewey H.; and Sujith, R. I.: "Exact Solution for the Free Vibration of a Rotating Cord with a Tip Mass," *Journal of Sound and Vibration*, vol. 181, no. 5, Apr. 13, 1995, pp. 911 – 914. (CERT related)

Hodges, Dewey H.: "Comment on 'Flexural Behavior of a Rotating Sandwich Tapered Beam' and on 'Dynamic Analysis for Free Vibrations of Rotating Sandwich Tapered Beams,'" *AIAA Journal*, vol. 33, no. 6, June 1995, pp. 1168 – 1170. (CERT related)

Hodges, D. H.; Shang, X.; and Cesnik, C. E. S.: "Finite Element Solution of Nonlinear Intrinsic Equations for Curved Composite Beams," *Journal of the American Helicopter Society*, submitted, June 1995.

Papers Presented at Conferences

Smith, Marilyn J., and Hodges, Dewey H.: "Development of an Aeroelastic Method for Hovering Rotors with Euler/Navier-Stokes Aerodynamics," *Proceedings of the 51st Annual Forum of the American Helicopter Society*, Fort Worth, Texas, May 9 – 11, 1995. (CERT related)

Hodges, D. H.; Shang, X.; and Cesnik, C. E. S.: "Finite Element Solution of Nonlinear Intrinsic Equations for Curved Composite Beams," *Proceedings of the 36th Structures, Structural Dynamics and Materials Conference*, New Orleans, Louisiana, Apr. 10 – 12, 1995, AIAA Paper 95-1174, pp. 103 – 112.

Hodges, Dewey H.; and Bless, Robert R.: "On an Analogy Between Beam Contact Problems and Optimal Control Theory with State Constraints," *Proceedings of the 36th Structures, Structural Dynamics and Materials Conference*, New Orleans, Louisiana, Apr. 10 – 12, 1995, AIAA Paper 95-1273, pp. 1011 – 1019. (CERT related)

Shang, X.; and Hodges, D. H.: "Aeroelastic Stability of Composite Rotors in Hover," *Proceedings of the 36th Structures, Structural Dynamics and Materials Conference*, New Orleans, Louisiana, Apr. 10 – 12, 1995, AIAA Paper 95-1453, pp. 2602 – 2610.

Shang, Xiaoyang; and Hodges, Dewey H.: "Aeroelastic Stability of Composite Hingeless Rotors with Advanced Configurations in Hover," *Proceedings of the 37th Structures, Structural Dynamics and Materials Conference*, Salt Lake City, Utah, April 15 – 17, 1996, AIAA Paper 96-1548, to appear.

<u>Presentations</u>:

Shang, Xiaoyang; and Hodges, Dewey H.: "Aeroelastic Stability of Composite Hingeless Rotors with Advanced Configurations," Presented at the 6th International Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, Los Angeles, California, November 8 – 10, 1995.

SM1. Structures and Materials Task
Dynamic Modeling of Composite Beams Including Edge-Zone Behavior

Co-PI's: Dewey H. Hodges and Victor L. Berdichevsky [1]

Background

In the last five-year portion of the Georgia Tech CERWAT program (1/88 – 1/93), the framework for a complete nonlinear theory of anisotropic beams was developed. This theory includes geometrically-exact kinematical and kinetical equations, along with a compatible and completely general cross-sectional analysis methodology. For composite rotor blades, cross-sectional modeling (two-dimensional) makes use of the material distribution and geometry of the blade cross section to obtain the appropriate properties to use in a beam (one-dimensional) analysis. In Task SM1 of the current phase of work for the rotorcraft center, now called CERT, research along these lines was continued. This work is important to the Army and to the rotorcraft industry because of their need for realistic modeling capability for composite rotor blades. While there are other ongoing investigations which address rotor blade modeling, this approach is unique in that the cross-sectional modeling and corresponding beam theory stem from the same foundation. To our knowledge, this approach is the only beam analysis methodology which is unified, asymptotically correct, based on a nonlinear framework from the outset, and applicable to cross sections with arbitrary geometry.

For interior static modeling of composite beams, the displacement field can be adequately described in terms of six variables and their derivatives: three displacement variables and three section rotation variables. It is well known that, for certain types of blades, this sort of beam theory cannot achieve an adequate degree of realism. For example, in the vicinity of a fixed end of the beam where the warping is constrained, the strain and stress vary rapidly along the spanwise coordinate, thus necessitating the retention of more variables in the beam theory than are required to correctly predict the interior behavior. This is because the characteristic length over which the deformation varies along the beam is much smaller than the beam length. This situation commonly occurs in the types of structures found in modern bearingless rotor flexbeam designs.

It would be tempting to attack the problem based on this purely static motivation. However, when one investigates dynamic response in which high-frequency modes are involved, the theory breaks down when the wave length becomes of the same order as the maximum cross-section dimension. Although this particular situation does not present as critical a problem in rotor blade dynamics, per se, it is theoretically analogous to the above static problem in that the driving mechanism for the breakdown of the interior static theory is the rapid spanwise variation of three-dimensional field variables along the beam reference axis.

Scope of Work

In order to remedy this, we are developing asymptotically correct one-dimensional theories which will generalize considerably the fidelity of the theory for these and other types of problems in the simplest manner possible. We are applying the variational-asymptotical method of Berdichevsky (1979) to the three-dimensional strain *and* kinetic energies of a beam. A minimum number of appropriate one-dimensional variables will be identified which will give good agreement with the dispersion curves derived from the three-dimensional total energy. This

---

1 Supported by subcontract to Wayne State University, Detroit, Michigan

method was shown in later work by Berdichevsky to result in an accurate model of the dynamics and restrained warping behavior of isotropic beams.

With this extension, the theory will be more accurate near the ends, especially when the warping is restrained. Furthermore, it should extend the frequency regime in which accurate results are obtained to a level far beyond the present theories. By attacking it as a dynamic problem, we not only solve the problem of immediate concern to practical *static* modeling of composite rotor blade flexbeams, but we obtain a consistent theory for high-frequency dynamics whose applications go beyond the modeling of helicopter rotor blades to other problems of interest to the Army, such as high-frequency dynamics of composite turbine blades, gun barrels, and manipulators.

Summary of Accomplishments

We first developed the theory to the point of identifying a special set of cross-sectional eigenfunctions which can be used to represent the displacement field. They are special because they guarantee that any warping induced by "sectional degrees of freedom" chosen as amplitudes for these "mode shapes" will be of a higher order than the displacement itself, which is important in finding the second approximation in a simplified manner. These eigenfunctions incorporate an immense amount of information about the cross section, such as its material makeup and its geometry. Thus, all discontinuities which exist in the strain or stress components are correctly accounted for. These eigenfunctions will provide the basis for excellent beam models. The theory was coded in VABS (our finite element cross-sectional analysis – *V*ariational-*A*symptotical *B*eam *S*ection) to the point that we could calculate these cross-sectional eigenfunctions. The code is based on isoparametric 6- and 8-noded quadrilateral elements. The first numerical results for stiffnesses based on the eigenfunctions were validated by comparison with analytical solutions for simple cases and against NABSA (see Giavotto et al. 1983) for laminated beams with extension-twist and an extension-bending couplings. The theory and some results are documented in the papers and presentations listed below. Results show two important phenomena: (1) The frequency associated with the cross-sectional eigenfunction may *not* be a reliable indicator of the importance of a mode. (2) Short-wavelength extrapolation is required to obtain a workable theory. For the latter to be undertaken requires a three-dimensional dispersion analysis.

A computer code for calculating three-dimensional dispersion curves for beams with arbitrary anisotropy, non-homogeneity and cross-sectional geometry was then developed for beams with arbitrary anisotropy, non-homogeneity and cross-sectional geometry. The generalized eigenvalue problem associated with the problem of finding dispersion curves is neither positive nor negative definite, and is a non-symmetric complex problem. The size of the matrices involved in the calculations requires preservation of the sparse structure of the original matrices as much as possible. A two-sided Lanczos algorithm for generalized eigenvalue problems was adopted, which employs a Harwell solver for a system of linear equations instead of the explicit inversion of the matrix, with respect to which left and right Lanczos vectors are being bi-orthogonalized. Precision of this calculation falls drastically if we try to calculate more than the first 6 – 12 roots. However, taking into consideration the fact that the roots obtained are symmetrical with respect to both imaginary and real axes, it turns out that only 3 – 4 distinct roots are needed. A shift in the complex plane and calculation of the roots closest to the initial (complex) guess for k allows any branch of a dispersion curve to be followed by making a small step with respect to Ω and using k obtained in the previous step as an initial guess. The amount of manual labor needed to use the code was at first substantial, but it has now been substantially reduced. Namely, the code presently assures automatic tracking of the branch all the way to an intersection with another branch, even if there is another branch located in a close proximity, and thus avoids jumping from one branch to another in the case of two branches approaching each other under small

angles. More complicated points of intersection of more than two branches still need human monitoring; fortunately, such intersections are not common.

As an application, work concentrated on thin-walled open cross sections where the influence of non-classical high-frequency and short-wavelength phenomena are particularly important. Dispersion pictures for both isotropic and anisotropic cases for an I-beam were obtained. Results for the isotropic case were compared to results based on Vlasov theory, which revealed a remarkable coincidence of the first non-classical branch (not only qualitatively but even quantitatively). This comparison has led to the idea that a correct description of the first non-classical branch by one-dimensional theory is easily attainable, because the warping for this branch can be approximated by the same kinematical relations as classical branches. A study was then undertaken to ascertain the reasons for the accuracy of Vlasov's theory. If this can be understood, it is then more likely that a general one-dimensional theory can be extracted from the dispersion analysis. The results have so far indicated that Vlasov's theory is for all intents and purposes asymptotically correct. Slight differences between it and an asymptotically correct theory only appear for cross sections that do not exhibit a large Vlasov effect in the first place.

There is still more work that needs to be done, and a proposal is under consideration for funding by the NRTC at the time of the writing of this report.

External Interactions

Due to the fundamental nature of this work, discussions with industry about practical applications would be premature. However, we have been in touch with all four major helicopter companies (Dr. Jing Yen, Bell; Mr. Frank Tarzanin, Boeing; Mr. Jerry Miao, Sikorsky, and Dr. Friedrich Straub, McDonnell Douglas Helicopters) to offer them the VABS software and training on how to use it. The offer was also extended to the windpower community through the U.S. Department of Energy (Dr. Gunjit Bir). We have also continued to interact with Dr. Gene Ruzicka and Dr. M. J. Rutkowski of the 2GCHAS Project office, U.S. Army Aeroflightdynamics Directorate, Ames Research Center. Although the primary aspect of this interaction has been the nonlinear beam element of the 2GCHAS system, provided by the first P.I., there has also been some discussion about VABS. Additional improvements to VABS are being undertaken in a project funded by the CERT Augmentation Grant, task RSI4.

Publications

Refereed Journals:

Cesnik, Carlos E. S.; and Hodges, Dewey H.: "Variational-Asymptotical Analysis of Initially Curved and Twisted Composite Beams," *Applied Mechanics Reviews*, vol. 46, no. 11, part 2, Nov. 1993, pp. S211 – S220.

Cesnik, Carlos E. S.; and Hodges, Dewey H.: "Variational-Asymptotical Analysis of Initially Twisted and Curved Composite Beams," *International Journal for Engineering Analysis and Design*, vol. 1, no. 2, Apr. 1994, pp. 177 – 187.

Cesnik, Carlos E. S.; and Hodges, Dewey H.: "Stiffness Constants for Composite Beams Including Large Initial Twist and Curvature Effects," *Applied Mechanics Reviews*, vol. 48, no. 11, part 2, Nov. 1995, pp. S61 – S67.

Cesnik, Carlos E. S.; Sutyrin, Vladislav G.; and Hodges, Dewey H.: "Refined Theory of Twisted and Curved Composite Beams: The Role of Short-Wavelength Extrapolation," *International Journal of Solids and Structures*, to appear, 1995.

Cesnik, C. E. S.; Hodges, D. H.; and Sutyrin, V. G.: "Stiffness Constants for Composite Beams Including Large Initial Twist and Curvature Effect," *AIAA Journal*, to appear, 1995.

Cesnik, Carlos E. S.; and Hodges, Dewey H.: "VABS: A New Concept for Composite Rotor Blade Cross-Sectional Modeling," *Journal of the American Helicopter Society*, submitted, June 1995.

Papers Presented at Conferences

Cesnik, Carlos E. S.; and Hodges, Dewey H.: "Stiffness Constants for Initially Twisted and Curved Composite Beams," *Proceedings of the 3rd Pan-American Congress of Applied Mechanics*, São Paulo, Brazil, Jan. 5 – 8, 1993, pp. 592 – 595.

Cesnik, Carlos E. S., Sutyrin, Vladislav G., and Hodges, Dewey H.: "A Refined Composite Beam Theory Based on the Variational-Asymptotical Method," AIAA Paper 93-1616. *Proceedings of the 34th Structures, Structural Dynamics, and Materials Conference*, La Jolla, California, Apr. 19 – 22, 1993, pp. 2710 – 2720.

Cesnik, Carlos E. S.; Sutyrin, Vladislav G.; and Hodges, Dewey H.: "Refined Theory of Twisted and Curved Composite Beams: The Role of Short-Wavelength Extrapolation," AIAA Paper 94-1451, *Proceedings of the 35th Structures, Structural Dynamics and Materials Conference*, Hilton Head, South Carolina, Apr. 20 – 22, 1994, pp. 1134 – 1143.

Cesnik, Carlos E. S.; and Hodges, Dewey H.: "Stiffness Constants for Composite Beams Including Large Initial Twist and Curvature Effects," *Applied Mechanics in the Americas (Proceedings of the 4th Pan-American Congress of Applied Mechanics,* Buenos Aires, Argentina, Jan. 3 – 6, 1995), vol. III, pp. 229 – 232.

Volovoi, V. V.; Berdichevsky, V. L.; Hodges, D. H.; and Sutyrin, V. G.: "Dynamic Dispersion Curves for Non-Homogeneous, Anisotropic Beams with Cross Sections of Arbitrary Geometry," *Proceedings of the 36th Structures, Structural Dynamics and Materials Conference*, New Orleans, Louisiana, Apr. 10 – 12, 1995, AIAA Paper 95-1445, pp. 2508 – 2514.

Cesnik, C. E. S.; Hodges, D. H.; and Sutyrin, V. G.: "Stiffness Constants for Composite Beams Including Large Initial Twist and Curvature Effect," *Proceedings of the 36th Structures, Structural Dynamics and Materials Conference*, New Orleans, Louisiana, Apr. 10 – 12, 1995, AIAA Paper 95-1500, pp. 3106 – 3116.

Cesnik, Carlos E. S.; and Hodges, Dewey H.: "VABS: A New Concept for Composite Rotor Blade Cross-Sectional Modeling," *Proceedings of the 51st Annual Forum of the American Helicopter Society*, Fort Worth, Texas, May 9 – 11, 1995.

Volovoi, Vitali V.; Hodges, Dewey H.; Berdichevsky, Victor L.; and Sutyrin, Vladislav G.: "Edge Effects in Thin-Walled Beams," *Proceedings of the 37th Structures, Structural Dynamics and Materials Conference*, Salt Lake City, Utah, April 15 – 17, 1996, AIAA Paper 96-1604, to appear.

Presentations:

Hodges, Dewey H.; Cesnik, Carlos E. S.; and Sutyrin, Vladislav G.: "A General Framework for Static and Dynamic Analysis of Initially Twisted and Curved Composite Beams," Presented at the Army Research Office Beamology Workshop, U.S. Army Aeroflightdynamics Directorate, Ames Research Center, Moffett Field, California, Oct. 13, 1992.

Hodges, Dewey H.: "Static and Dynamic Analysis of Initially Twisted and Curved Composite Beams," Presented at the Workshop on Structural Dynamics Issues for Comprehensive Analysis of Rotorcraft, Johnson Aeronautics, St. Louis, Missouri, May 18, 1993.

Atilgan, Ali R.; Berdichevsky, Victor L.; Cesnik, Carlos E. S.; Hodges, Dewey H.; and Sutyrin, Vladislav G.: "High-Frequency Composite Beam Dynamics," U.S. Army Research Office Workshop on Dynamics of Composites, New Orleans, Louisiana, Aug. 30 – Sept. 1, 1993.

Cesnik, Carlos E. S.; Sutyrin, Vladislav G.; and Hodges, Dewey H.: "A Refined Composite Rotor Blade Theory Based on the Variational-Asymptotical Method," Presented at the 5th Army Research Office Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, Troy, New York, Oct. 18 – 20, 1993.

Hodges, Dewey H.; Cesnik, Carlos E. S.; Sutyrin, Vladislav G.; Berdichevsky, Victor L.; and Volovoi, Vitali V.: "Sectional Modeling of Composite Rotor Blades for Static and Dynamic Analysis," Presented at the U.S. Army Research Office Comprehensive Analysis Workshop, U.S. Army Aeroflightdynamics Directorate, Ames Research Center, Moffett Field, California, Mar. 6, 1995.

Berdichevsky, Victor L.; Sutyrin, Vladislav G.; Hodges, Dewey H.; and Volovoi, Vitali V.: "Vlasov Theory: Is it Asymptotically Correct?," Presented at the 6th International Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, Los Angeles, California, November 8 – 10, 1995.

SM3. Damage Characterization and Analysis for Unsymmetrical Composite Laminates

Co-PI's: Erian Armanios and George Kardomateas

Background

The primary objective of this research is the characterization of the damage modes associated with unsymmetric laminates subjected to static and dynamic loading.

Final Report:

This report is an overview of the research performed in this task. It describes the motivation, major accomplishments, the lessons learned and future investigation which stems from its findings.

Motivation

The motivation for studying unsymmetric composites is based on a number of considerations. The first, is concerned with the modeling of realistic composite structures which possess some kind of unsymmetry due to manufacturing tolerances and defects. The second, is service related damage which alter the initial symmetry of a composite design. This induced unsymmetry should be considered in order to ensure the composite damage tolerance. The third, is the flexibility unsymmetric composites provides through elastic tailoring. The coupling that unsymmetric configurations create between deformation modes provide an extra degree of freedom to meet the design requirements efficiently and economically.

In order to implement the benefits of unsymmetric composites, three major challenges have to be addressed. The first, is the development of analytical models to predict their response under mechanical and hygrothermal loading. The second, is concerned with their manufacturing and the need to accommodate the warping deformations associated with the curing cycle. The third, is the development of test methods which allow accurate measurements of the degrees of freedom resulting from the coupling.

These challenges have been addressed in the present task. The major accomplishments in analysis, manufacturing and testing are summarized in the following. Of significance is the fact that the simultaneous consideration of these three components of the research was critical in achieving a basic understanding of the behavior and performance of unsymmetric composites. A prime example is the role that test results played in underscoring the importance of including a number of physical effects in the development of the analytical models. These effects are not considered in classical theories applied to composites.

Major Accomplishments

As a result of the capability of the shear deformation sublaminate approach developed under the previous [*1*] for free-edge delamination of unsymmetric composites, the theory was extended to model internal delaminations. While free-edge delaminations are mainly controlled by manufacturing defects and loading, internal delaminations include the effect of low energy impact as well. The phenomena of interlaminar stress driven free-edge delamination has been extensively studied and documented. Fewer studies by comparison, have been devoted to internal delamination. The present model identifies and predict the effect of internal delamination on the stiffness and strength of a composite structure and consequently ensures its damage tolerance by allowing for a more complete analysis of a damaged structure. The developed theory is presented in Refs. *2* and *3*.

In order to verify the accuracy of the developed theory a class of hygrothermally stable laminate unsymmetric laminates proposed by Winckler at RPI [*4*] were manufactured and tested. The material used was T300/954-3 Graphite/Cyanate. Two sets of four laminates each with and without embedded internal delamination were manufactured in order to assess the influence of damage on the extension-twist coupling. The major challenge in the testing was to provide a simple, accurate and repeatable means for the laminate ends to twist freely while subjected to axial loading. To this end three methods [*5*] have been developed under a parallel Grant. The test method adopted in this work is the improved custom build apparatus which allows free end twist using compressed air [*6*]. The apparatus fits into a universal testing machine. The accuracy of the improved apparatus is unaffected by load and the maximum load capacity is approximately 9 KN. The resolution of the output angle is $\pm 0.1^\circ$ with a maximum hysteresis of 0.2°. The high resolution is accomplished by using an optical encoder for angle measurement.

As a result of the test method used which allows accurate free end twisting rotation of the laminate a distinct nonlinear trend was observed in the extension-twist data. Earlier test data [*5*] did not exhibit such distinct nonlinear behavior and correlated quite well with the shear deformation theory developed in Ref. *2* and a linear finite element simulation. An investigation into the cause of the nonlinear behavior revealed that is due to the finite rotation of the laminate as extension load is applied. A geometrically nonlinear analysis for flat and pretwisted laminates was developed in Refs. *7* and *8*. This analysis provides a closed form expression for the extension-twist force relationship and shows excellent correlation with test data as depicted in Figs. 1 and 2 for two different layups. To our knowledge, this is the first closed form expression accounting for finite displacement in laminated composite strips.

Lessons Learned and Future Investigation

Among the findings of this research task, a number of lessons have significant implications. The first, is the influence of internal versus free-edge delaminations on the failure of unsymmetric laminates. Internal delaminations are less critical than free-edge delaminations as shown by the interlaminar stress profiles and strain energy release rate. This is of practical significance since low energy impact induces internal delaminations which are not often detected. The second, is the significance of geometric nonlearity in modeling unsymmetric laminates exhibiting extension-twist coupling. The contribution of the axial force to the twisting moment plays a significant role in the nonlinear behavior of axial force versus twist angle. This finding is depicted in Figs. 1 and 2 where the approximate model corresponding to neglecting the contribution of axial force does not depict the nonlinear behavior of the test data and is indistinguishable from the linear solution.

The significance of geometric nonlinearity in the extension-twist coupling of undamaged laminates underscores the need for investigating the influence of material nonlinearity as well. Test results on unsymmetric laminates made of C30/922 Graphite/Epoxy material system exhibited a much smaller nonlinear behavior [*5*].

The influence of internal delaminations showed a marginal reduction on the extension-twist coupling of the laminate. A result which does not agree with analytical predictions and finite element simulations. A preliminary investigation indicated that the major reason is associated with the use of Teflon film to simulate delamination. Such a technique is widely used for fracture toughness measurements. It was found that the Teflon film surface is nonplanar as a result of the cure cycle and consequently transmits interfacial stresses. This issue is critical to the accurate simulation of stress-free delamination surfaces and experimentally measured fracture toughness under mixed mode behavior. An investigation into the means of achieving accurate controlled delaminated surfaces in tests is needed. Once this is achieved the significance of geometric and material nonlinearities on the extension-twist coupling could be accurately assessed.

These tasks have been proposed under the NRTC Rotorcraft Center of Excellence.

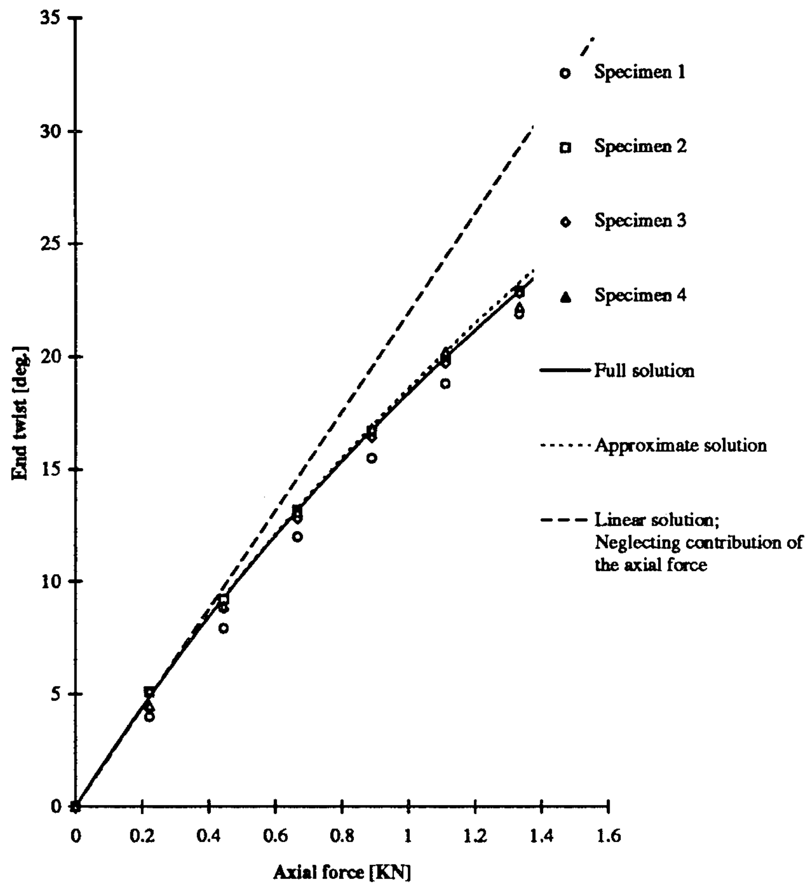


Fig. 1- Comparison of Twist Predictions with Test Data $[30_2/-60_4/30_2/30_2/-60_4/30_2]_T$ Laminate

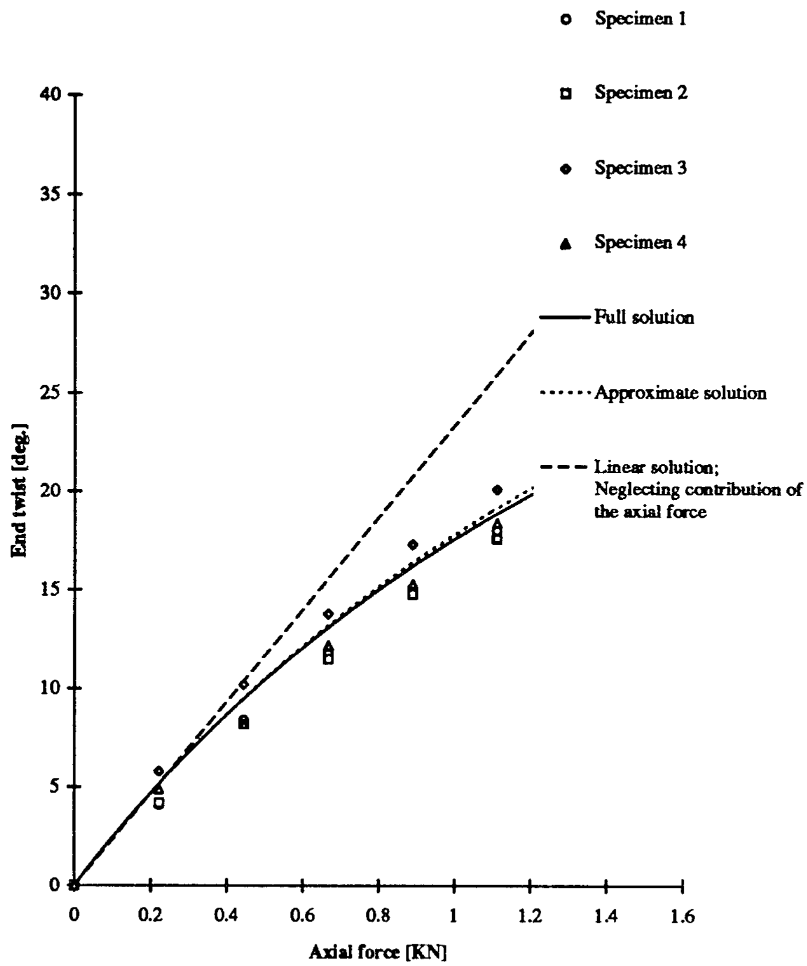


Fig. 2- Comparison of Twist Predictions with Test Data $[20_2/-70_4/20_2/20_2/-70_4/20_2]_T$ Laminate

References

[*1*] Armanios, E. A. and Li, Jian, "Interlaminar Fracture Analysis of Unsymmetrical Laminates," *Composite Materials: Fatigue and Fracture, Fourth Volume, ASTM STP 1156*, W. W. Stinchcomb and N. E. Asbaugh, Eds., American Society for Testing and Materials, Philadelphia, 1993, pp. 341-360.

[2] Palmer, David W., "The Effect of Internal Delamination on Unsymmetric Laminated Composite Plates," Ph. D. Thesis, School of Aerospace Engineering, Georgia Institute of Technology, 1995.

[*3*] Palmer, D. W., Armanios, E. A. and Hooke, D. A." Fracture Analysis of Internally Delaminated Unsymmetric Laminated Composite Plates," *ASTM Sixth Symposium on Composites: Fatigue and Fracture*, Denver, Colorado, May, 16-17, 1995. Submitted for publication in *ASTM Sixth Symposium on Composites: Fatigue and Fracture* STP

[4] Winckler, S. I.(1985) "Hygrothermally Curvature Stable Laminates with Tension-Torsion Coupling," *Journal of the American Helicopter Society*, Vol. 31, No. 7, pp. 56-58.

[5] Hooke, D. A. and Armanios, E. A., "Development of Three Methods for Testing Extension-twist Coupled Laminates," ASTM Twelfth Symposium on Composite Materials: Testing and Design, Montreal, Quebec, May 1994, to be published in an ASTM Special Technical Publication. to appear in ASTM STP 1274.

[6] Hooke, D. A. and Armanios, E. A., " Rotational Displacement Apparatus with Ultra-Low Torque and High Thrust Load Capability, " U.S. Patent Pending.

External Interactions

The geometrically nonlinear model and results have been communicated to Dr. Joy Sen at McDonnell Douglas Helicopter Systems and Dr. T. Kevin O'Brien at ARL, NASA Langley. An independent testing program is underway using the biaxial testing machine at NASA Langley. This is aimed at providing an assessment of test data generated using the custom build apparatus. A Cooperative Research Agreement based on the NRTC task between ARL and Georgia Tech is being ratified.

Publications During the Grant Period:

Refereed journals:

1. Parnas, L., Armanios, E. A., Sriram, P. and Rehfield, L., "Postbuckling and Crippling of I-Section Composite Stiffeners," *Journal of Aerospace Engineering*, Vol. 8, No. 1, January, 1995, pp. 32-42.

2. Armanios, E. A., Hooke, D., Kamat, M., Palmer, D., and Li, J., "Design and Testing of Composite Laminates for Optimum Extension-Twist Coupling," *Composite Materials: Testing and Design (Eleventh Volume), ASTM STP 1206*, E. T. Camponeschi, Jr., Ed., American Society for Testing and Materials, Philadelphia, 1993, pp. 249-262.

3. Li, J., and Armanios, E. A.," Influence of Free-Edge Delaminations on the Extension-Twist Coupling of Elastically Tailored Composite Laminates," *Mathl. Comput. Modeling*, Pergamon Press, Vol. 19, No. 3/4, pp. 89-107, 1994.

4. Sriram, P. and Armanios, E. A., "Shear Deformation Analysis of the Energy Release Rate of Transverse Cracking in Laminated Composites," *Composite Materials: Fatigue and Fracture (Fifth Volume), ASTM STP 1230*, Roderick H. Martin, Ed., American Society for Testing and Materials, Philadelphia, 1995, pp. 215-231.

5. Hooke, D. A. and Armanios, E. A., "Development of Three Methods for Testing Extension-twist Coupled Laminates," to appear in *Composite Materials: Testing and Design (Twelfth Volume)*, ASTM STP 1274.

Meeting Papers:

1. Uda, N., Parnas, L. and Armanios, E. A., "Stress Field in Postbuckled Composite Stiffeners Loaded in Compression," *Advanced Composites ' 93, International Conference on Advanced Composites*, Edited by T. Chandra and A. K. Dhingra, The Minerals, Metals & Materials Society, 1993, pp. 315-321.

2. Badir, A. M., Berdichevsky , V. and Armanios, E. A.," Theory of Anisotropic Thin-Walled Opened-Cross-Section Beams," *34th AIAA/ASME/AHS/ASC Structures, Structural Dynamics and Materials (SDM) Conference*, La Jolla, CA, April 19-21, 1993, pp. 2761-2770.

3. Berdichevsky, V., Armanios, E. and Badir, M., "A New Look at Thin-Walled Composite Beam Modeling," *Ninth International Conference on Composite Materials (ICCM 9)*, Madrid, Spain, July 12-16, 1993, Vol. III, pp. 219-226.

4. Li, J. and Armanios, E. A., "Effect of Damage on an Elastically Tailored Laminated Composite Plate," *Ninth International Conference on Composite Materials (ICCM 9)*, Madrid, Spain, July 12-16, 1993, Vol. VI, pp. 728-735.

5. Armanios, E. A., "Elastically Tailored Composites: Analysis Design and Testing," Proceedings of the *U. S.-Russian Workshop on Computer Synthesis of Structure and Properties of Advanced Composites*, Moscow, Russia, May 10-11, 1994, pp. 194-218.

22. Palmer, David W., and Armanios, Erian A., "The Effect of Internal Delamination on the Extension Twist Coupling in Elastically Tailored laminated Plates," Proceedings of the *26th International SAMPE Technical Conference*, Atlanta, Georgia, October 24-27, 1994, pp. 128-141.

Papers and Abstracts Submitted/Accepted:

1. Palmer, D. W., Armanios, E. A. and Hooke, D. A." Fracture Analysis of Internally Delaminated Unsymmetric Laminated Composite Plates," Submitted for publication in *ASTM Sixth Symposium on Composites: Fatigue and Fracture* STP.

2. Armanios, E. A. and Makeev, A., "Finite Displacement Analysis of Laminated Composite Strips with Extension-twist Coupling. I: Flat Strips" Submitted for publication, J. Aerosp. Engrg., ASCE.

3. Armanios, E. A., Makeev, A., and Hooke, D. A., "Finite Displacement Analysis of Laminated Composite Strips with Extension-twist Coupling. II: Pretwisted Strips" Submitted for publication, J. Aerosp. Engrg., ASCE.

4. Li, J. and Armanios, E. A., "Analysis of Free-Edge Delamination in Unsymmetrical Composite Laminates," to appear in *Fracture of Composites*, Trans Tech Publications, 1996

5. Armanios, E. A., Hooke, D. A., and Makeev, A., "Testing and Geometrically Nonlinear Analysis of Pretwisted Laminated Composite Strips with Extension-twist Coupling," accepted for presentation, ASTM thirteenth Symposium on Composite Materials: Testing and Design, Orlando, FLA, May 12-14, 1996

Ph.D. Thesis:

Palmer, David W., "The Effect of Internal Delamination on Unsymmetric Laminated Composite Plates," Ph. D. Thesis, School of Aerospace Engineering, Georgia Institute of Technology, 1995.

Special Problem:

Calcaterra, J. ," Damage Tolerance of Light Sandwich Composites," Special Problem Report Submitted in partial fulfillment of the requirements for the M.Sc. degree, School of Aerospace Engineering, Georgia Institute of Technology, August, 1993.

Awards :

1. David Hooke, 1995 Winner of SAIC Student Technical Paper and E. Armanios Certificate of Award in honor of contributions, made as advisor to the technical paper entitled: "Examination of Three Methods for Testing Extension-Twist Coupled Laminates."

2. D. Stefan Dancila, 1995 Winner of the Luther S. Long III Memorial Award in Engineering Science & Mechanics.

3. Refereed paper #4, Selected to highlight advancement on Damage in Structural Configurations in *Materials Technology, A strategic Industry Report on the Synthesis, Processing, and Applications of Advanced Materials*, Elsevier, November 1993, Vol. 8, Numbers 11/12, pp. 263-264.

IV. FLIGHT MECHANICS & CONTROLS

Task FMC1 Rotorcraft Simulation Math Model Fidelity Issues

Faculty: J.V.R. Prasad, D.A. Peters, A. Calise, D.P. Schrage
Participants: Wen-Ming Cao, Jerry Higman, Ketao Liu, Martin Stettner - GRAs

Objectives/ Background

This task includes 3 topics addressing rotorcraft simulation mathematical model fidelity issues. Rotor and propulsion system dynamics along with interactional aerodynamics produce an extremely complex high order system. Research is needed to better understand the simulation requirements.

1. Interactional Aerodynamics

Our approach is to use the maturity and flexibility of the finite-state wake model for representing wake-body interference effect in flight simulations. We completed comparison of two approaches. The Φ^A method was found to work only on the disk and could not be extended. The ϕ^V method gave reasonable answers except within the rotor wake. To this end, we computed vortex-lattice results and compared them with the F^V method to determine the needs for off-disk application of the theory.

2. Rotor-Engine Coupled Model

Our approach is to investigate the required number of degrees of freedom and adequately represent the nonlinear coupling terms between engine and rotor dynamics for simulation evaluation of integrated flight/propulsion controllers. Ketao Liu completed his disseration proposal during this period, and is currently completing his thesis work. The bulk of this report deals with this work.

Existing flight/propulsion controller designs are based on scope-limited and expensive flight tests or simplified model simulations.
In this project, a detailed study of dynamic couplings between helicopter rotor and propulsion system through analysis and simulation has been conducted. First, a novel modeling approach is used in developing a component model of a turboshaft engine typically used in modern rotorcraft. Then the model is analyzed and simplified using an interface analysis approach such that the model is incorporated into the coupled engine/rotor model with necessary dynamics. After validation of the turboshaft engine model, a simulation model of the combined helicopter and engine system is
constructed. Using such a simulation model, the effects of each degree of freedom of the engine on its dynamic coupling with the rotor and the vehicle are studied. Simulation results bring out some of the significant couplings between the engine and the rotor. Some further detailed analysis using linearized models has been undertaken.

Mathematical Modeling For Turbo Shaft Engine:

For this project, a general turboshaft engine model is developed first by using a novel engine modeling approach adopted from the method presented in Eveker's Ph.D. thesis. The general model is then applied to the T700GE700 turboshaft engine to form a system consisting of 21 ordinary differential equations. In order to incorporate the necessary dynamics into the coupled engine/rotor model, a novel interface dynamics analysis approach is developed. Based on the results from interface analysis, the T700GE700 engine model is then simplified into a six

degree model, which consists of two spool dynamic equations, namely, the compressor spool and the power turbine spool equations, one heat sink dynamic equation and three equations for the compressor flow dynamics. The simplification of the engine model is realized after residualizing some of the subcomponent dynamics which have little contribution to engine/rotor coupling. The resulting six degree T700GE700 engine model is validated against experiment data and it is found out that the engine parameters have a maximum relative error of 3.0%.

Coupled Engine/Rotor Model:

Two engine/rotor coupling model are constructed using the previously developed T700GE700 engine model. A simplified coupled engine/roto model is constructed first by coupling the further simplified T700GE700 engine model with a simplified rotor model. The purpose of constructing this simplified coupled engine/rotor model is to investigate the adequacy of using a linear engine model for this project and also to make initial understanding of the significance of each degree of freedom of the coupled engine/rotor dynamics in the coupled engine/rotor behavior. The simplified engine/rotor model consists of a turboshaft engine model component (the compressor flow dynamics is residualized), a simplified rotor model component (a three degree model), a nonlinear static throttle model component to connect the collective input to the fuel flow, and a proportional controller which modifies the fuel flow to the engine within limits in proportion to the change of the main rotor speed from a nominal value. The block diagram of this simplified coupled engine/rotor model is shown in Figure 1.

Since the simplified coupled engine/rotor model is limited for further understanding of coupled engine/rotor characteristics, a detailed coupled engine/rotor model is constructed using the previously developed six degree T700GE700 engine model and the software system FLIGHT LAB as a platform. As shown in Figure 2, the detailed model consists of several subsystem models, namely a main rotor model, a tail rotor model, an airframe model, a flight control system model, an aero-interference model and a propulsion system model.

Implementation and Conclusions:

The coupled engine/rotor dynamic analysis is carried by implementing the two coupled engine/rotor models using numerical simulations. The simplified coupled engine/rotor model is implemented as a SIMULINK program. Simulations are done with the model parameters of an Apache main rotor and the T700GE700 turboshaft engine. Both open loop and closed loop dynamic responses are obtained at hover condition with two typical inputs, namely a doublet collective stick input and a step collective stick input. The following conclusions are obtained from analysis of the dynamic responses:

a. Linear engine model is not adequate for coupled engine/rotor dynamics analysis.
b. Heat sink dynamics has significant influences on the system transient responses.
c. Compressor spool dynamics plays a very important role in the engine/rotor dynamic coupling.
d. Main rotor shaft elasticity has little influence on the engine/rotor dynamic coupling in open loop response.
e. Dynamic inflow has very small influence on the engine/rotor coupling.
f. Rotor first torque mode is sensitive to the controller gain.

The detailed coupled engine/rotor model is implemented by using FLIGHT LAB as a platform. Simulation is carried out with model parameters of UH-60 Black Hawk helicopter. Only open loop simulation is carried out. A doublet collective stick input and a doublet pedal stick input are used for the simulation.

Simulation results indicate that:

g. With a doublet collective stick input, engine dynamics has significant influence on vehicle body lateral acceleration response.
h. With a doublet collective stick input, engine dynamics has significant influence on vehicle body roll rate response.

I. With a doublet collective stick input, engine dynamics has significant influence on vehicle body yaw rate response.

j. With a doublet pedal input, engine dynamics has significant influence on vehicle body vertical acceleration response.

However, since these results are input dependent, further analytical studies are needed in order to identify the characteristics of the coupled engine/rotor dynamic behavior.

3. Physical Model Validation Techniques

Here we have been developing guidelines for physical fidelity (model component behavior) of simulator models. The results have been presented at the 1995 AHS Annual Forum.

Degrees Granted During the Project Period

PhDs

Jesse Leitner Received PhD in June 1995.

M.S.

Liu, Ketao	Currently PhD student
A. Lipp	Joined in Fall'90. Graduated in Winter 92.
M.de la Fuente	Received MS in 1992. Design and Implementation of a Digital Control System to Control the Rotational Movement of a Motor Driven Flexible Beam
J. Leitner	Received MS in 1992. Synthesis of a Helicopter Full Authority, Nonlinear Flight Controller using Feedback Linearization and Model Inversion

Journal Publications During this Period

1. Mittal, M. and Prasad, J.V.R., "Input-Output Linearization of a Three Dimensional Model of a Twin-Lift Helicopter System," Journal of Guidance, Control and Dynamics, Vol 16, No.1, pp. 86-95, January 1993.
2. Riaz, J., Prasad, J.V.R., Schrage, D.P., Gaonkar, G.H., "Atmospheric Turbulence Simulation for Rotorcraft Applications," Journal of the American Helicopter Society, Vol. 38, No.1, pp. 84-88, January 1993.
3. Prasad, J.V.R. and Lipp, A., "Synthesis of a Helicopter Nonlinear Controller using Approximate Model Inversion," International Journal on Mathematical and Computer Modeling, Vol. 18, No. 3/4, pp. 89-100, 1993.

Conference Papers

1. Prasad, J.V.R. and Lipp, A., "Synthesis of a Helicopter Nonlinear Flight Controller using Approximate Model Inversion," Paper presented at the AIAA Guidance, Navigation and Control Conference, Hilton Head, SC, August 1992.

Conference Papers (cont'd)

2. Leitner, J. and Prasad, J.V.R., "Helicopter Robust Nonlinear Controller Synthesis using Approximate Linearization," Proceedings of the 1993 Annual Forum of the American Helicopter Society, May 1993.
3. Scholz, C. and Prasad, J.V.R., "Propulsion System Modeling for Integrated Flight Propulsion Control Study" Proceedings of the 1994 Annual Forum of the AHS, May 1994.
4. Leitner, J., Prasad, J.V.R., Calise, A.J., "Helicopter Robust Flight Control System Development using Neural Networks," AIAA GNC Conference, August 1994.
5. Jiang, T.Y., Prasad, J.V.R. and Swaminathan, R., "Synthesis of an Integrated Fuzzy/Nonlinear Controller for Rotorcraft," AHS Forum, May 1995.
6. Prasad, J.V.R. et al., "Coupled Flap-Lag Rotor Blade Load Identification". Proceedings of the AHS Annual Forum, Ft. Worth, TX, May 1995.
7. Prasad, J.V.R. et al., "Aeroelastic Tailoring of a Civil Tiltrotor Configuration". AHS Vertical Lift Aircraft Design Conference, San Francisco, CA January 18-20, '96.

External Interactions

Collaboration with Bill Bousman, AFDD on work related to UH-60 Airloads data.
Interaction with ATCOM, St. Louis, in obtaining the T700-GE-700 Engine geometric data.
Discussions were held at the 50th Annual Forum of AHS with NATC personnel regarding development of rotorcraft models using FLIGHTLAB software.

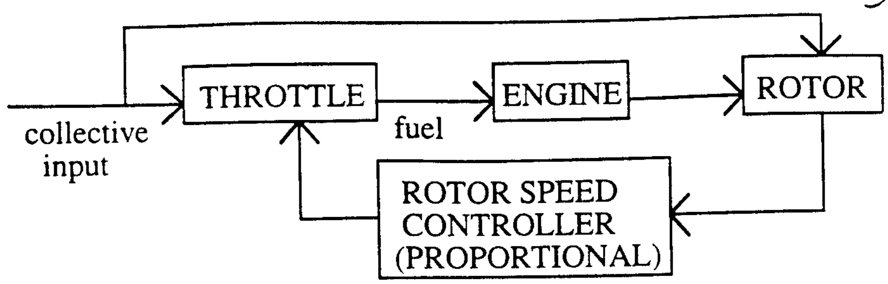

THROTTLE
ENGINE
ROTOR
collective input
fuel
ROTOR SPEED CONTROLLER (PROPORTIONAL)

Fig. 1.

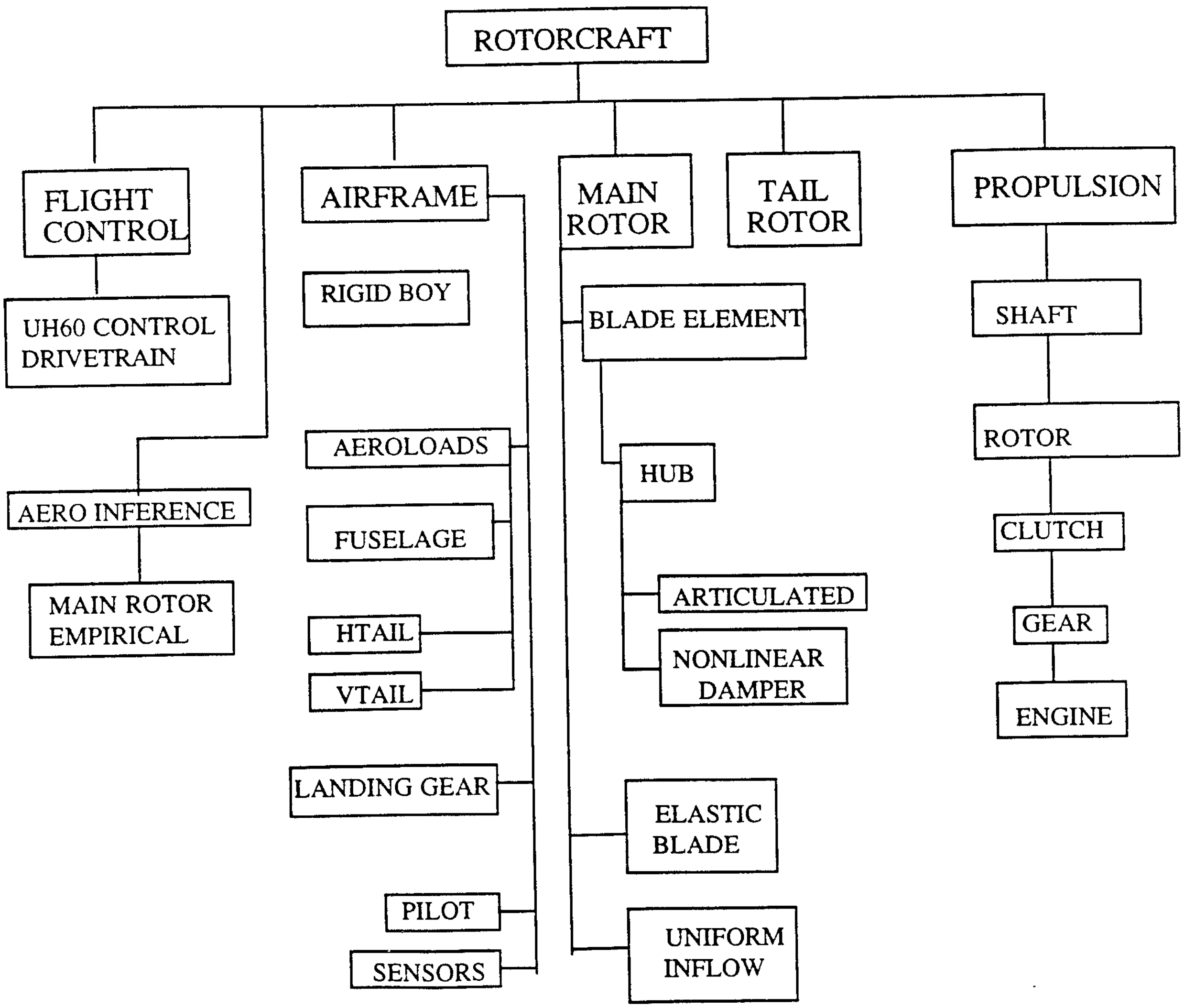

ROTORCRAFT
FLIGHT CONTROL
AIRFRAME
MAIN ROTOR
TAIL ROTOR
PROPULSION
UH60 CONTROL DRIVETRAIN
RIGID BOY
BLADE ELEMENT
SHAFT
AEROLOADS
ROTOR
HUB
AERO INFERENCE
FUSELAGE
CLUTCH
MAIN ROTOR EMPIRICAL
ARTICULATED
GEAR
HTAIL
NONLINEAR DAMPER
VTAIL
ENGINE
LANDING GEAR
ELASTIC BLADE
PILOT
UNIFORM INFLOW
SENSORS

Fig. 2.

IV. FMC (2). Research in Robust Control Theory

Principal Investigators: A.J. Calise, J.V.R. Prasad and D.P. Schrage

Subtask 2.1 Linear Control (A.J. Calise)

Problem Studied

This task is devoted to exploring robustness and controller order reduction issues related to the design of rotorcraft flight control systems The objectives are to develop a methodology for designing fixed order dynamic compensators in an optimal output feedback setting. The design approach should allow for a direct means of trading off performance and robustness measures.

Summary of Results

Having completed the major theoretical aspects of fixed order H-infinity design, and its extension to the mixed H2/H-infinity design problem, the focus of our work during the past three years shifted to address the computational aspects associated synthesizing fixed order designs based on the necessary conditions that have been derived for these problems, and extentions of our work to both complex and real mu-synethesis. We first explored a conjugate gradient algorithm. However, this algorithm requires extensive experience (and patience) on the part of the user. The two major difficulties are 1) selecting an initial guess and 2) reliable convergence to a solution point. Following this initial work, we embarked in a new direction to develop a homotopy algorithm. The homotopy approach parameterizes the problem in such a way that it becomes easy to initialize the search (select and initial guess and find an initial solution) when the parameter is set to zero. The homotopy then consists of following a solution path as the parameter (p) varies from zero to one. The solution at p=1.0 corresponds to the solution to the actual problem. In addition to providing an easy method for forming an initial guess, the approach is much more reliable (computationally robust) because it uses both gradient and hessian information, and because it always remains within a small neighborhood of the solution path. Many of the problems we have tried are now solved without user intervention, although there are some cases which have encountered a near singularity along the solution path.

During the second year we presented three papers at the 1994 AIAA Guidance, Navigation and Control Conference. One paper provides the theoretical development of the necessary conditions for the fixed order H-infinity and mixed H2/H-infinity problems (Sweriduk & Calise). This paper includes numerical results on a helicopter flight control problem. A second paper describes the homotopy algorithm and evaluates it using an 8th order problem - a flexible structure with four degrees of freedom (Whorton, Buschek & Calise). This paper develops the homotopy approach for the H2 as well as the H-infinity problem and the mixed H2/H-infinity problem. Some of the results for this problem were briefly described in our second year progress report. A third paper illustrates the use of the algorithm to design low dimensional H-infinity controllers and a mu controller for a 17th order flight control example (Buschek & Calise). Due to the complexity of the problem, several approaches to robustify the numerical procedure were developed for this application.

During the third year, we focused on extending the current fixed order H-infinity design procedure to fixed order mu-synthesis. In mu-synthesis, optimal full order H-infinity controllers (K) and D-scaling matrices (D) that account for the structure in the uncertainty are computed iteratively. Since frequency dependent D-scales are augmented to the plant for controller design, the resulting mu controller tends to be of rather large order. By replacing the full order controller design step in the D-K iteration procedure of mu-synthesis with the developed fixed order

homotopy algorithm, we are able to design robust controllers which are less conservative and of low dimension. We have also carried standard mu-synthesis one step further by introducing real parameter uncertainty in addition to the complex uncertainty representation in standard mu-synthesis. This is the so-called mixed mu-synthesis problem. Additional "G-scales" were introduced which account for the phase information of real parameter uncertainty and enable a refinement of the upper bound on the structured singular value, mu. Thus, the conservatism introduced when real uncertainty is treated as complex is reduced. This new approach of designing fixed order mu controllers for mixed real/complex uncertainties was applied to a well known benchmark problem, a flexible satellite example, and to the Apache AH64 helicopter model near hover. A paper was presented at the 1995 AIAA Guidance, Navigation and Control Conference (Buschek & Calise) that describes the methodology and applies it to the benchmark problem and to a flexible satellite example. To date, the helicopter application has only been documented in a Ph.D. thesis (H. Buschek). An application to hypersonic flight vehicle control has also been treated via this approach and presented at the Sixth International Aerospace Planes and Hypersonic Technologies Conference.

A brief discription of the application to the benchmark problem follows. The benchmark problem is a two mass/springk system which has been extensively studied in the literature from the perspective of robust control. First, full order designs were performed for both complex and mixed mu controllers. Uncertainty in spring stiffness was the focus of the robust design. The objective is to reduce peak response to an impulsive disturbance for the uncertainty range in stiffness of $0.5<k<2.0$. This resulted in a 12th order complex mu design and a 16th order mixed mu design. Fig. 1 compares the performance of these designs. Note that the mixed mu design results in a lower peak response, and is less sensitive to stiffness reduction. The complex mu design results in oscillations for k=0.5. Fig. 2 shows that the nominal (k=1) control effort is also significantly reduced for the mixed design.

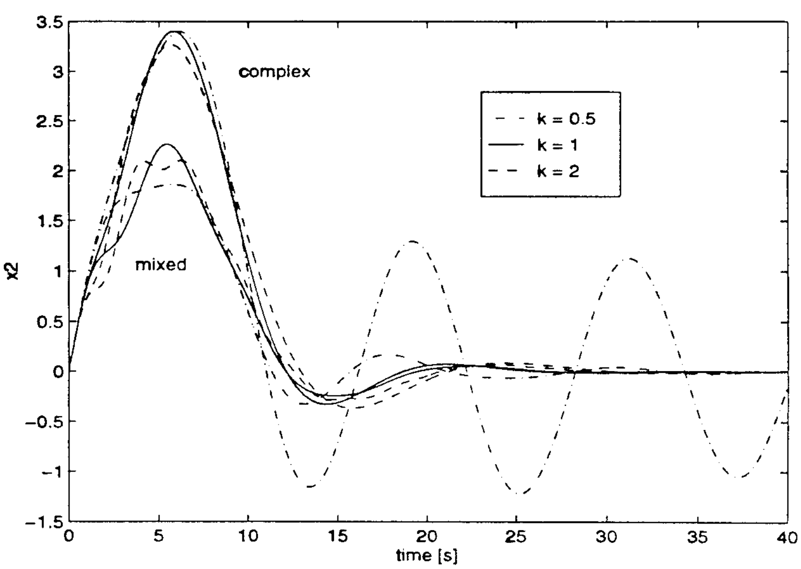


Fig. 1 Response of full order controllers with varying spring stiffness.

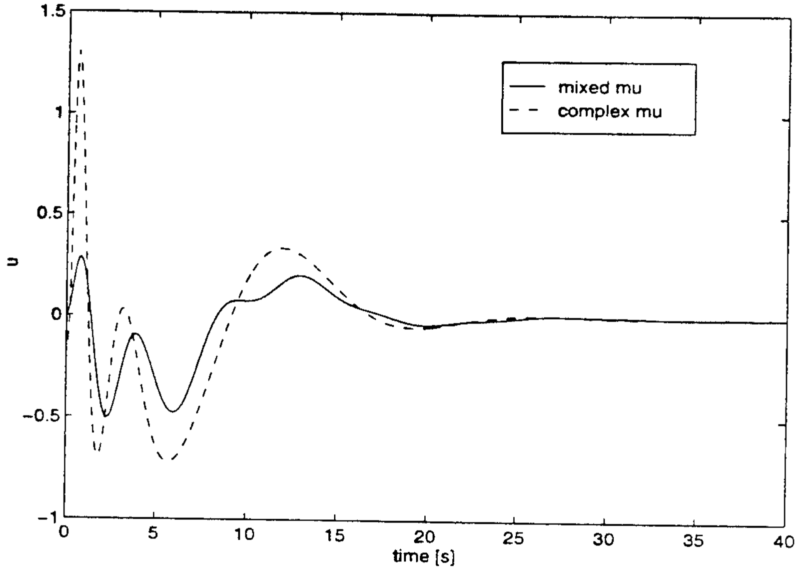


Fig 2. Control effort for full order controllers (k=1.0).

Employing a balanced model reduction scheme, the mixed mu controller could be reduced to 3rd order. However, this incresed the upper mu bound from 1.32 for the full order design to 3.62 for the reduced design, indicating a significant loss of robust performance. Using this reduced mu controller as a starting guess for the fixed order design algorithm, the upper mu bound was reduced to a value very close to that of the full order design. The upper mu bounds are compared in Fig. 3. Consequently, it is possible to design a 3rd order controller with negligable loss in robust performance. Performance comparisons for the 3rd order reduced controller and the optimized 3rd order fixed controller are given in Fig. 4. The reduced order controller leads to oscillations for all values of k and exhibits a trend to a steady-state error. The optimized fixed order design essentially reproduces the full order responses of Fig. 1.

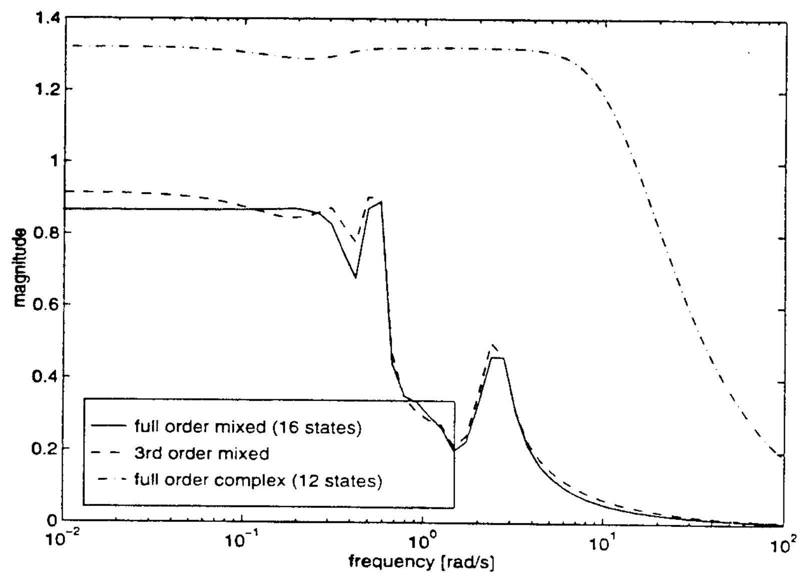


Fig. 3 Comparison of the upper mu bounds

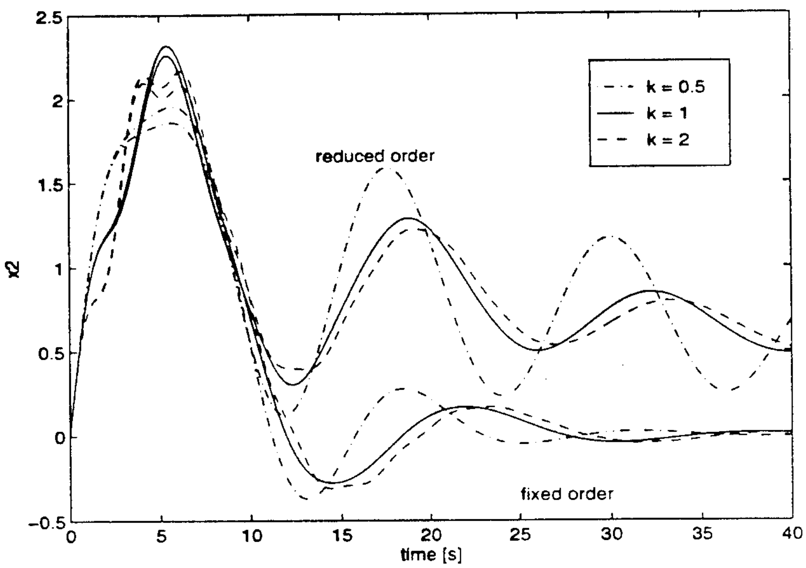


Fig. 4. Response of 3rd order controllers with varying spring stiffness.

Subtask 2.2 Nonlinear Control (A.J. Calise & J.V.R. Prasad)

Problem Studied

Most techniques for synthesis of modern flight controls employ linear control theory. Despite the successful application of this design methodology to a wide variety of flight vehicles, the overall gain-scheduled system typically comes with no guarantees of full envelope stability and performance. In hopes of overcoming some of the limitations and drawbacks of linear controller design, a variety of nonlinear flight control techniques have been researched. Among these, the feedback linearization technique has received much of the attention and shows great promise. In this method, the vehicle dynamic model is first transformed to a linear time invariant form using feedback measurements. Control laws are then synthesized using linear multi-variable system theory. Back transformation of the synthesized control law to the original coordinates produce a globally stabilizing nonlinear feedback law. The most significant aspect of this synthesis method is that gain scheduling becomes unnecessary. However, the primary difficulty associated with application of the feedback linearization for air vehicle control is that a detailed knowledge of the nonlinear plant dynamics is required.

Artificial neural networks and fuzzy control offer the potential to overcome the difficulties associated with limited knowledge of the nonlinear plant dynamics through a combination of both off-line and on-line (i.e. in flight) learning. Neural networks with on-line learning can also adapt to changes in aircraft dynamics, i.e. changes in configuration and partial loss in control effectiveness. In addition, neural networks in the flight control architecture offer speed in performing the model inversion required to implement feedback linearization since massive parallel processing is done in a neural network.

Summary of Results in Neural Networks

We have completed the theoretical development and numerical investigation of a direct adaptive tracking control architecture using neural networks. A stable weights adjustment rule

for a neural network was derived that can be implemened in real time. This rule was derived using Lyapunov stability theory in the presence of bounded neural network realization error. Under mild assumptions on the nonlinearities representing the inversion error, the adaptation algorithm assures that all the signals in the adaptive loop are uniformly bounded when a dead zone is applied, and that the weights of the second neural network tend to constant values. A paper related to this aspect of the research was presented at the 1994 AIAA Guidance, Navigation and Control Conference (Kam & Calise). This paper carries out a complete 6DOF evaluation for the F-18 fighter aircraft.

Following this development, we carried out a detailed evaluation using a TMAN model of the AH-64 helicopter. Subsequent studies were focused on using the FLIGHTLAB simulation of the same helicopter model. The results generated using the TMAN simulation were presented at the CDC conference in December (Calise, Kim, Leitner & Prasad). Figures 5 and 6 give a brief summary. The maneuver starts in hover. The results were generated using the following sequence of commands: (1) a step command in roll attitude from the initial trim attitude to zero degrees, (2) a negative pitch pulse to accelerate the vehicle to approximately 60 ft/s, (3) three complete heading revolutions while maintaining zero pitch and roll attitude (elliptic turn maneuver), and (4) bring all attitudes to zero. Figure 4 compares the pitch and roll responses and their corresponding cyclic controls with and without the on-line network. Note in particular the dramatic improvement in roll response. Figure 6 illustrates the effect of the adaptation gain. Note that the roll response is stable and monotonically improves with increasing adaptation gain. This feature will be of significant importance in a flight test environment, where it will be desirable to gradually increase the authority of the on-line adaptive network.

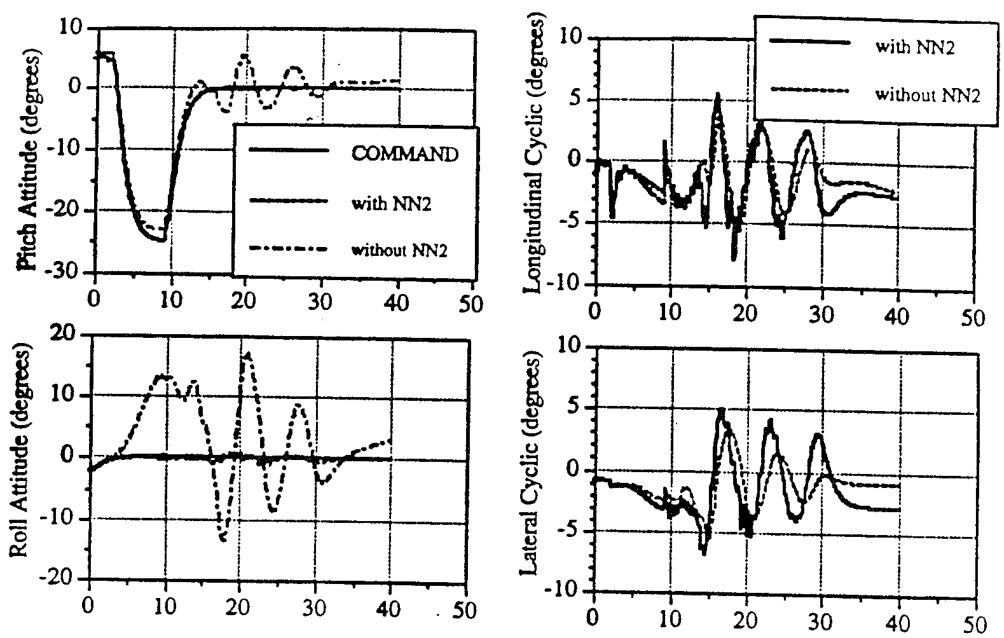


Figure 5. Simulated responses with and without the neural network.

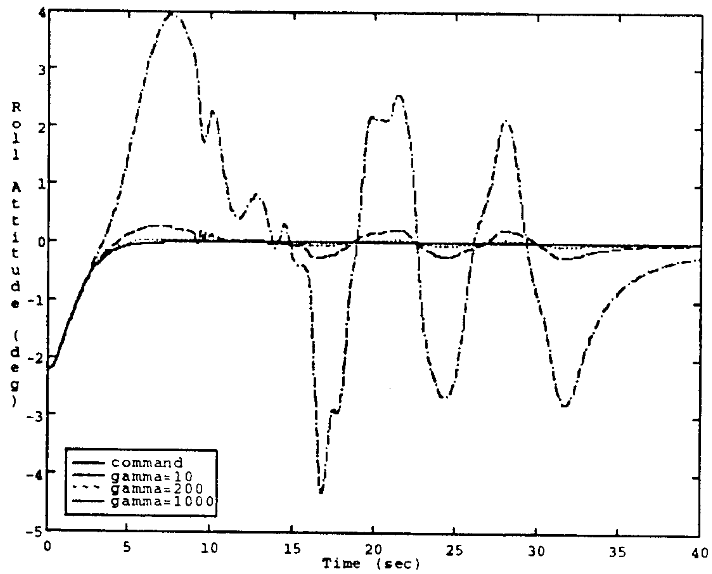


Figure 6. Effect of varying the adaptation gain on the roll attitude response.

The FLIGHTLAB simulation model of the Apache helicopter is a comprehensive highly nonlinear model which includes rotor dynamics, dynamic inflow, and elastic modes for the blades as well as other significant dynamics which are unmodeled in the controller. Because of the complexity and modularity of the model, there is no analytical state space model from which to synthesize a controller. An approximate model was obtained using input-output data from the simulation, as would be done from an actual helicopter. A linear aerodynamic model was generated at the hover flight condition and was used as a nominal model for the controller. The kinematic nonlinear terms which represent transformations between coordinate systems are maintained in the nominal controller. The nominal controller is synthesized based on a complete time scale separation between inner (rotational states) and outer (translational states) loop dynamic inversions. The linear dynamics are chosen to have a 0.875 damping ratio and 0.5 rad/sec natural frequency for the outer loop and a heavily damped inner loop with damping ratio of 2.0 and natural frequency of 2.7 rad/sec. The heavy damping in the inner loop is found to be necessary for achieving satisfactory inner loop tracking performance.

In order to correct for 'inversion errors' caused by variations in the nominal model, an on-line, adaptive neural network is augmented to correct for the inner loop inversion error only, because the (fast) inner loop tracking errors are the most significant errors in the closed loop system and can also cause larger magnitude errors in the slow outer loop. The network employed is relatively simple, with the inputs being the body states u,v,w,p,q,r and the collective perturbation (from hover trim value), all appearing linearly. These inputs correct the feedback terms due to variations in the linear aerodynamic model throughout the flight path. A large adaptation gain of 2100 is used with the network, comparable to the rates used in previous applications of this work using the TMAN simulation. The superior tracking performance of the adaptive neural network controller is clearly evident from simulation results. For example, Fig. 7 compares the roll attitude tracking performance during an elliptical turn maneuver with and without the neural network. Inner loop tracking performance is significantly enhanced by the network.

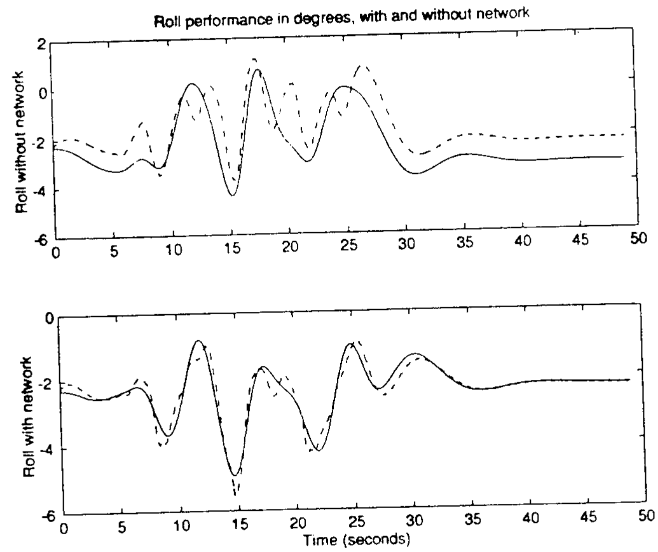


Fig. 7 Comparison of roll performance using the FLIGHTLAB simulation.

In comparing Fig. 7 with the results from TMAN (Fig's. 5 and 6) it is important to keep in mind that the TMAN results were generated with the outer loop open, while the FLIGHTLAB results were generated with the outer loop closed. Closure of the outer loop has the effect of diminishing the inner loop tracking errors in the no network results. This was also observed using the TMAN simulation. Therefore, when the roll response was studied using the TMAN simulation, it was decided to conduct the study with the outer loop open to amplify the problem associated with the network implementation that existed at that time.

Summary of Results in Fuzzy Control

During the later part of our 3 year project we initiated a study on exploring the use of fuzzy control synthesis techniques for helicopter full envelope flight controller development. Towards this, we have synthesized a simple fuzzy controller to replace parts of the outer loop of the model inversion controller. The synthesized fuzzy controller converts longitudinal and lateral position commands into required pitch and roll attitudes, which are then used as commands to the inner loop inversion controller. Fuzzy rules are developed using Δu and $\dot{u}$ (where $\Delta u = u_{command} - u_{actual}$ and $\dot{u}$ is the acceleration along the x-body axis) for obtaining the required pitch attitude and Δv and $\dot{v}$ (where $\Delta v = v_{command} - v_{actual}$ and $\dot{v}$ is the acceleration along the in y-body axis) for obtaining the required roll attitude. Synthesis of the attitude control loops and the vertical position loop is based on the previously developed model inversion technique. The performance of such a hybrid fuzzy nonlinear model inversion controller was evaluated through simulation using the TMAN simulation program.

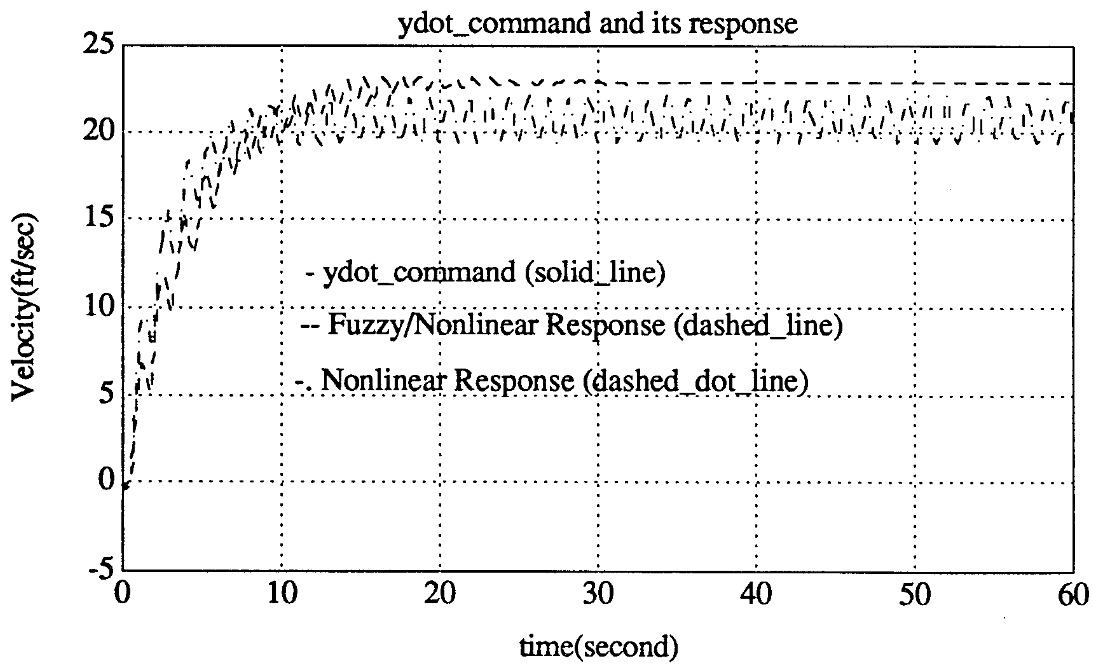


Figure 8. Helicopter response to a step lateral speed command.

Figure 8 compares helicopter response to a step lateral speed command using a hybrid fuzzy nonlinear controller with that of the model inversion controller in the presence of modeling uncertainties. Both results were obtained by taking the parameters in the aerodynamic model used for control computations equal to 10% of the simulation model values. It is clear from Figure 8 that the hybrid controller is able to accommodate large changes in model parameters.

Though not shown, similar results were obtained for step longitudinal speed commands as well. A paper related to these results was presented at the 1995 Annual Forum of the AHS.

Conference Publications in Linear Control

1. Sweriduk, G.D., Calise, A.J., "A Differential Game Approach to the Mixed H2/H∞ Problem," AIAA Guidance, Navigation, and Control Conference, AIAA-94-3660, Scottsdale, AZ, August 1994.

2. Whorton, M., Buschek, H., and Calise, A.J, "Homotopy Algorithms for Fixed Order H2 and H∞ Design," AIAA Guidance, Navigation, and Control Conference, AIAA-94-3661, Scottsdale, AZ, August 1994. Submitted for publication in AIAA J. of Guid., Contr. and Dynamics.

3. Buschek, H., Calise, A.J., "Fixed Order Robust Control Design for Hypersonic Vehicles," AIAA Guidance, Navigation, and Control Conference, AIAA-94-3662, Scottsdale, AZ, August 1994.

4. Buschek, H., Calise, A.J., "μ Controllers: Mixed and Fixed," AIAA Guidance, Navigation, and Control Conference, AIAA-95-3238, Baltimore, MD, August 1995.

5. Buschek, H., Calise, A.J., "Hypersonic Flight Control System Design Using Fixed Order Robust Controllers," Sixth International Aerospace Planes and Hypersonic Technologies Conf., Chattanooga, TN, 1995.

Conference Publication in Nonlinear Control

1. Kim, B., Calise, A.J, "Nonlinear Flight Control Using Neural Networks," AIAA Guidance, Navigation, and Control Conference, AIAA-94-3646, Scottsdale, AZ, August 1994. Accepted for publication in AIAA J. of Guid., Cont. and Dynamics.

2. Leitner, J., Prasad, J.V.R., and Calise, A.J., "Nonlinear Control of Rotorcraft Using Approximate Feedback Linearization and On-line Neural Networks," AIAA Guidance, Navigation, and Control Conference, AIAA-94-3693, Scottsdale, AZ, August 1994.

3. Calise, A.J., Leitner, J., and Prasad, J.V.R., "Helicopter Adaptive Flight Control Using Neural Networks," 33rd IEEE Conference on Decision and Control, Lake Buena Vista, FL, Dec. 1994.

4. Leitner, J., Calise, A.J., and Prasad, J.V.R., "Analysis of Adaptive Neural Networks for Helicopter Flight Controls," AIAA Guidance, Navigation, and Control Conference, AIAA-95-3268, Baltimore, MD, August 1995.

5. Jiang, T.Y. and Prasad, J.V.R., "Synthesis of an Integrated Fuzzy/Nonlinear Controller for Rotorcraft," 1995 Annual Forum of the American Helicopter Society, May 1995.

Journal Publications

1. Prasad, J.V.R. and Lipp, A.L., "Synthesis of a Helicopter Nonlinear Flight Controller Using Approximate Model Inversion," Journal of Mathematical and Computer Modeling, Vol. 18, No. 3/4, August 1993, pp. 89-100.

2. Byrns, E.V., Calise, A.J., "Approximate Recovery of H-infinity Loop Shapes Using Fixed-Order Dynamic Compensation," AIAA J. of Guidance, Control, and Dynamics, May-June 1994, pp. 458-465.

Theses

1. Kim, B-S., "Nonlinear Flight Control Using Neural Networks," Georgia Institute of Technology, School of Aerospace Engineering, December 1993.

2. Sweriduk, G. "Robust Control with Fixed-Order Dynamic Compensators: A Differential Game Approach," Georgia Tech, School of Aerospace Engineering, May 1994.

3. Leitner, J. "Helicopter Nonlinear Control using Adaptive Feedback Linearization," Ph.D. Thesis Proposal, Georgia Tech, School of Aerospace Engineering, April 1994.

4. Buschek, H., "Synthesis of Fixed Order Controllers with Robustness to Mixed Real/Complex Uncertainties," Georgia Tech, School of Aerospace Engineering, February 1995.

Collaborations

Dr. Calise was awarded a collaborative effort by NASA Ames to explore the benefits of neural networks and inverse control for reducing pilot workload and increasing safety of operations for tiltrotor aircraft operating in the terminal area. It is expected that advancing our research to piloted simulations will provide a major stimulus to identifying cooperative efforts with the helicopter industry.